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Robust Congestion Control Using Sliding Mode Control In TCP/IP Computer Networks

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ABSTRACT

Based on the recent Internet advances, congestion control is considered as an important issue and has spurred a significant amount of research. In this study, second-order sliding mode control is used to adjust the average queue length and maintain the closed-loop system performance. The control law is obtained in two steps. First, the nonlinear state-space form of the network is extracted based on state variables as the average queue length and congestion window size. Then, the proportional-Integrator-derivative and proportional- derivative sliding surface are defined according to the tracking error. Also, in order to avoid chattering, the derivative of the sliding surface is considered and the closed-loop system stability is investigated based on Lyapunov theory. The proposed scheme renders good tracking specifications and closed-loop system robustness. The simulation results show that the proposed methods outperform proportional integral (PI) and proportional integral derivative (PID) schemes. Also, robustness to disturbances increases and chattering and transient response degradation are avoided.

Article Info

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I. INTRODUCTION

A set of protocols is defined as TCP/IP reference model to enable end-to-end (E2E) communications over the Internet. The Transmission Control Protocol (TCP) is an Internet standard which is utilized by many applications[1]. In [2], the scalable TCP is established as a Multiplicative Increase Multiplicative Decrease (MIMD) protocol. It explains the conditions where the total multiplicative increase dynamics of window size is transformed to an additive increase one. In [3], a framework is developed for networked TCP applications which supports both congestion avoidance and slow start algorithms. The aforementioned model addresses the router network which supports any Active Queue Management (AQM) techniques.

Congestion control is an important function which motivates wide acceptance of TCP. Congestion of packets at the outgoing queues in routers renders low reliability and network performance degradation. So, more effective congestion control schemes are needed. Since 1990s control theory has been applied to solve congestion problem in communication networks [4].

Recently, there has been a vast amount of research on using sliding mode control in congestion control schemes [5]-[12]. A TCP congestion control mechanism based on a sliding window mechanism where an additive increase multiplicative decrease (AIMD) algorithm is employed to fit the transmission rate to available network resources is

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introduced in [5], a TCP congestion control protocol which uses the congestion window growth function as an exponential function and introduces an adaptive increasing factor in the aforementioned function is established in [6], SMC to control congestion in TCP networks where stability analysis is assessed using Lyapunov theorem is assessed in [7], an adaptive generalized minimum variance (AGMV) as a congestion controller for dynamically varying TCP/AQM networks is presented in [8], sliding mode variable structure control (SMVS) is presented as a congestion controller for AQM in [9], an SMC based on TCP input–delayed model for AQM routers supporting TCP data transfer is established in [10], SMC for uncertain time delay TCP/AQM network systems is presented in [11] and an SMC technique to control congestion in differentiated service communication networks is addressed in [12].

Time delay could be found in different fields. In [13], delay and data loss compensation are studied in Internet-based process control systems, and Internet transmission delay is overcome by considering a variable sampling time. In this regard, two compensation elements in feedforward and feedback channels are presented. Delay can lead to epidemic outbreak in complex networks and it must be considered in the analysis of congestion control methods [14]. In [15], decentralized LMI-based strategies are presented in a delayed nonlinear network to control congestion. The schemes are robust to queue size changes and the consequent delay changes. Also, the control problem is solved using linear matrix inequalities (LMIs). The stability of a TCP/RED congestion control model is studied in [16] where delays are state-dependent and Random early detection (RED) is considered for Internet congestion control. However, RED parameters are difficult to study because of model discontinuous terms and delay.

During the last two decades, great attention has been paid to improving TCP congestion performance by considering slow start, congestion avoidance, fast retransmit, and fast recovery as the congestion control scheme modules. In [17], AQM schemes are used to evaluate TCP performance to control congestion where different TCP and AQM variants are studied. The study is conducted by a practical setup and shows the importance of choosing proper TCP and AQM variants. In [18], the bibliography of TCP/IP congestion control schemes in the last two decades is classified and some main results are obtained. In [19], a scalable testing method is presented for congestion control schemes in real-world TCP implementations where the TCP congestion control is either tested at the interface level or it is tested using an equivalence class of test inputs simultaneously.

In this study, second-order sliding mode control is used to adjust the average queue length and maintain the closed-loop system performance. In this strategy, the control law is obtained in two steps. Also, in order to avoid chattering, the sliding surface derivative is considered and the closed-loop system stability is investigated based on Lyapunov theory.

The reminder of this article is organized as follows: Section II summarizes the TCP/IP dynamic model. Sections III and IV present the sliding mode congestion controller for TCP/IP dynamic model based on sliding surface proportional-integrator-derivative (SSPID) and sliding surface proportional-derivative (SSPD), afterwards, in section V, the performance of our approach is assessed by a simulation set up, and finally section VI provides the conclusion of this paper.

II. Tcp/Ip Dynamic Model

Among different dynamic models which are developed for TCP/IP, the model by [20] is one of the most widely used models which incorporates the fluid flow and stochastic differential equations to represent TCP/IP dynamics. In the aforementioned model, the queue size and the congestion window size are considered as state variables. The model is expressed as follows:

$$\begin{aligned} \dot{w}(t) &= \frac{1}{R(t)} - \frac{w(t)}{2}\frac{w(t-R(t))}{R(t-R(t))}p(t-R(t)) \\ \dot{q}(t) &= N\frac{w(t)}{R(t)} - C \end{aligned} \tag{1}$$

where $w(t)$ is the TCP congestion window size (packets), $q(t)$ the queue size (packets), $R(t)$ the round-trip time (RTT) (seconds), C the link capacity (packets / sec), N the traffic load (the TCP session number) and finally $p(t)$ is the packet drop probability. In (1), the congestion window size and the queue size are considered as state variables. Also, the packet drop probability and the queue length are input and output signals, respectively. By considering $x_1(t) = w(t)$ and $x_2(t) = q(t)$ as state variables, $u(t) = p(t-R(t))$ as input signal and $y(t) = q(t)$ as system output, the network nonlinear state-space model is as follows:

$$\begin{aligned} \dot{x}_1(t) &= \frac{1}{R(t)} - \frac{x_1(t)}{2}\frac{x_1(t-R(t))}{R(t-R(t))}u(t) \\ \dot{x}_2(t) &= N\frac{x_1(t)}{R(t)} - C \end{aligned} \tag{2}$$

Also, RTT is the queue length function and we have:

$$R(t) = \frac{q(t)}{C} + \tau_p \tag{3}$$

where τ_p represents the propagation delay (seconds). So, the state-space model (2) can be written as:

$$\dot{x}_1(t)=\frac{1}{\left(\frac{x_2(t)}{C}+\tau_p\right)}-\frac{x_1(t)}{2}\frac{x_1(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{\left(\frac{x_2(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{C}+\tau_p\right)}u(t)$$
$$\dot{x}_2(t)=N\frac{x_1(t)}{\left(\frac{x_2(t)}{C}+\tau_p\right)}-C \tag{4}$$

There exist some constraints on the input signal and system states which shall be considered in the controller as a saturation function. The constraints are as follows:

$$0\le q(t)\le q_{\max}$$
$$0\le w(t)\le w_{\max} \tag{5}$$
$$0\le p(t)\le 1$$

where $q_{\max}$ is the queue capacity (packets) and $w_{\max}$ is the maximum congestion window size (packets).

III. Sliding Mode Congestion Controller for Tcp/Ip Dynamic Model

Sliding mode control (SMC) can be considered as an important control scheme which is robust to disturbances and modeling uncertainties. Since there exist uncertainties occurring in TCP/IP computer networks, SMC is suggested for congestion control in this paper. In this scheme, states should reach a sliding surface in a limited period of time and remain there. The queue length tacking error can be written as:

$$e(t)=q(t)-q_d=x_2(t)-x_{2d} \tag{6}$$

where q_d is the optimal average queue size. In this section, the sliding surface is considered as a sliding surface proportional -integrator- derivative (SSPID):

$$s(t)=\dot{e}(t)+\lambda_1 e(t)+\lambda_2\int_0^t e(t)d(t) \tag{7}$$

The sliding mode control ensures that system states converges to the sliding surface asymptotically in a limited time. The Lyapunov function is considered as:

$$v(t)=\frac{1}{2}s^2(t) \tag{8}$$

By derivating (8), we have

$$\dot{v}(t)=s(t)\dot{s}(t) \tag{9}$$

To ensure the stability of the closed loop system, (9) shall be negative. So, the inequality (10) is used:

$$\dot{v}(t)=s(t)\dot{s}(t)\le-\eta|s(t)|\rightarrow\dot{s}(t)\le-\eta\,\mathrm{sign}(s(t)) \tag{10}$$

Using (7), the sliding surface derivative is as follows

$$\dot{s}(t)=\ddot{e}(t)+\lambda_1\dot{e}(t)+\lambda_2 e(t) \tag{11}$$

Considering the tracking error (6), we have

$$\dot{s}(t)=\ddot{x}_2(t)-\ddot{x}_{2d}+\lambda_1\left(\dot{x}_2(t)-\dot{x}_{2d}\right)+\lambda_2\left(x_2(t)-x_{2d}\right) \tag{12}$$

Since we have

$$\ddot{x}_2(t)=N\frac{\dot{x}_1(t)}{\left(\frac{x_2(t)}{C}+\tau_p\right)}-\frac{N}{C}\frac{\dot{x}_2(t)x_1(t)}{\left(\frac{x_2(t)}{C}+\tau_p\right)^2}, \tag{13}$$

By substituting (2), we have

$$\ddot{x}_2(t)=N\frac{\left(\frac{1}{\left(\frac{x_2(t)}{C}+\tau_p\right)}-\frac{x_1(t)}{2}\frac{x_1(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{\left(\frac{x_2(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{C}+\tau_p\right)}u(t),\right)}{\left(\frac{x_2(t)}{C}+\tau_p\right)}-\frac{N}{C}\frac{\left(N\frac{x_1(t)}{\left(\frac{x_2(t)}{C}+\tau_p\right)}-C\right)x_1(t)}{\left(\frac{x_2(t)}{C}+\tau_p\right)^2} \tag{14}$$

So

$$\ddot{x}_2(t)=\frac{2N}{\left(\frac{x_2(t)}{C}+\tau_p\right)^2}-N\frac{-\frac{x_1(t)}{2}\frac{x_1(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{\left(\frac{x_2(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{C}+\tau_p\right)}u(t),}{\left(\frac{x_2(t)}{C}+\tau_p\right)}-\frac{N^2}{C}\frac{x_1^2(t)}{\left(\frac{x_2(t)}{C}+\tau_p\right)^3} \tag{15}$$

which can be rewritten as

$$\ddot{x}_2(t)=\Phi(x,t)+\Psi(x,t)u(t) \tag{16}$$

where

$$\Phi(x,t)=\frac{2N}{\left(\frac{x_2(t)}{C}+\tau_p\right)^2}-\frac{N^2}{C}\frac{x_1^2(t)}{\left(\frac{x_2(t)}{C}+\tau_p\right)^3}$$
$$\Psi(x,t)=-N\ -\frac{x_1(t)}{2\left(\frac{x_2(t)}{C}+\tau_p\right)}*\frac{x_1(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{\left(\frac{x_2(t)}{C}+\tau_p\right)\left(\frac{x_2(t-\left(\frac{x_2(t)}{C}+\tau_p\right))}{C}+\tau_p\right)} \tag{17}$$

So, the sliding surface derivative is:

$$\dot{s}(t)=\Phi(x,t)+\Psi(x,t)u(t)-\ddot{x}_{2d}+\lambda_1\left(\dot{x}_2(t)-\dot{x}_{2d}\right)+\lambda_2\left(x_2(t)-x_{2d}\right) \tag{18}$$

Considering (10), we have

$$\Phi(x,t)+\Psi(x,t)u(t)-\ddot{x}_{2d}+\lambda_1\left(\dot{x}_2(t)-\dot{x}_{2d}\right)+\lambda_2\left(x_2(t)-x_{2d}\right)\le-\eta\,\mathrm{sign}(s(t)) \tag{19}$$

In order to satisfy (18), the control signal is considered as follows

$$u(t)=\frac{1}{\Psi(x,t)}\left(-\Phi(x,t)+\ddot{x}_{2d}-\lambda_1\left(\dot{x}_2(t)-\dot{x}_{2d}\right)-\lambda_2\left(x_2(t)-x_{2d}\right)-k\,\text{sign}(s(t))\right) \quad (20)$$

In (20), k is sliding mode gain and plays a key role in dealing with uncertainties.

IV. Sliding Mode Congestion Controller for Tcp/Ip Dynamic MODEL

In this scheme, the sliding surface is considered as a sliding surface proportional -derivative:

$$s(t)=\dot{e}(t)+\lambda e(t) \quad (21)$$

The sliding surface derivative is defined as:

$$\dot{s}(t)=-k_1 s(t)-k_2\,\text{sign}(s(t)) \quad (22)$$

There exist two design parameters, namely, k_1, k_2 in (22). SMC suffers from the disadvantage of high frequency oscillations of the control signal which is considered as chattering. In case of using high order sliding mode control, increasing the sliding mode gain ends in chattering decrease in the control signal. By considering k_1, a stable dynamic is obtained for sliding surface derivative where the derivative of the sliding surface tends to be zero. To extract the SMC law, first, the sliding surface derivative is calculated. So, we have:

$$\dot{s}(t)=\ddot{e}(t)+\lambda e(t)=\Phi(x,t)+\Psi(x,t)u(t)-\ddot{x}_{2d}+\lambda\left(\dot{x}_2(t)-\dot{x}_{2d}\right) \quad (23)$$

Using Equ. (22), we have

$$\Phi(x,t)+\Psi(x,t)u(t)-\ddot{x}_{2d}+\lambda\left(\dot{x}_2(t)-\dot{x}_{2d}\right)=-k_1 s(t)-k_2\,\text{sign}(s(t)) \quad (24)$$

So, the SMC law is as follows:

$$u(t)=\frac{1}{\Psi(x,t)}\left(-k_1 s(t)-k_2\,\text{sign}(s(t))+\ddot{x}_{2d}-\lambda\left(\dot{x}_2(t)-\dot{x}_{2d}\right)-\Phi(x,t)\right) \quad (25)$$

In the following, by choosing the sliding surface derivative (22), Lyapunov stability is established. The Lyapunov function is considered as:

$$v(t)=\frac{1}{2}s^2(t) \quad (26)$$

So, we have:

$$\dot{v}(t)=s(t)\dot{s}(t)=s(t)\left(-k_1 s(t)-k_2\,\text{sign}(s(t))\right)=-k_1 s^2(t)-k_2 s(t)\,\text{sign}(s(t)) \quad (27)$$

Since

$$\begin{cases} s(t)\ge 0\rightarrow sign(s(t))=1\rightarrow s(t)sign(s(t))>0 \\ s(t)<0\rightarrow sign(s(t))=-1\rightarrow s(t)sign(s(t))>0 \end{cases} \quad (28)$$

so,

$$\dot{v}(t)=-k_1 s^2(t)-k_2 s(t)\,\text{sign}(s(t))\le 0 \quad (29)$$

The above inequality shows that if Equ. (22) is satisfied, the closed-loop system stability is guaranteed. In other words, (29) shows that the sliding surface converges to zero asymptotically. On the other hand, according to Equ. (6), if the sliding surface converges to zero, the tracking error will converge to zero asymptotically.

V. Performance Analysis

In this part, first the performance of SSPID and SSPD is studied. In this regard, changes in queue length, packet loss probability and the congestion window size and RTT are studied. Afterwards, the impact of disturbance is examined on the system performance. Finally, the results of the proposed controller are compared with PI and PID controllers.

A. Performance Analysis of the Proposed Controllers

In this part, the performance of SSPID and SSPD is studied in case of tracking of the desired queue length and packet drop probability. Also, the congestion window size, RTT, the sliding surface and its derivative are shown. The sliding mode controller sets the average queue length such that the system performance is guaranteed in the presence of external disturbances and model uncertainties. The simulations are run for the following network parameters: $N=60,\ C=3750,\ \tau_d=0.2$ .The parameters set in SSPID are $\lambda_1=16, \lambda_2=64, k=5$ and the parameters set in SSPD are $k_1=15,\ k_2=10,\ \lambda=20$. It is worth noting that the state variables and control signal are constrained in TCP-based computer network systems. Fig.1 shows the tracking of the desired queue length in SSPID and SSPD.

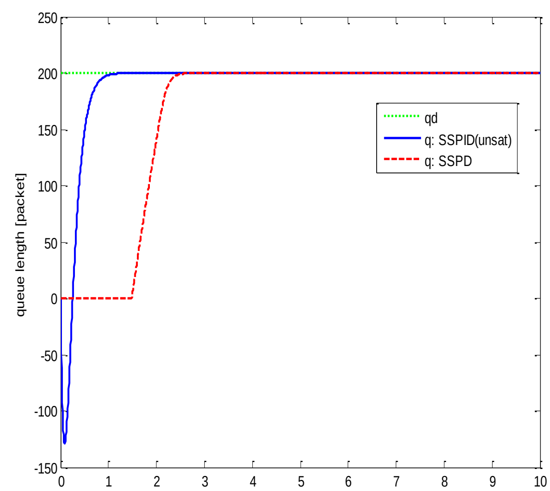

Fig. 1. Tracking of the desired queue size in in SSPD and SSPID

Fig. 1 shows the effect of saturation on the control signal and system states. The output converges to its desired level after the transient time. Fig. 2 shows the control signal.

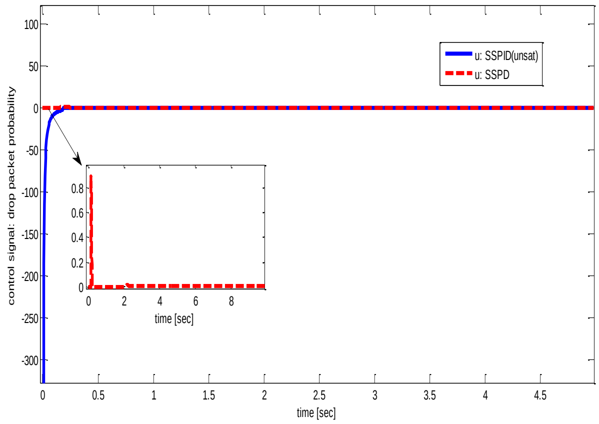

Fig. 2. Packet drop probability in in SSPD and SSPID

The control signal implies that the packet drop probability is high in transient time, however, it is reduced after the transient time. The packet drop probability in SSPD is less than that of in SSPID, so a better control signal is gained in SSPD comparing with SSPID. Fig. 3 shows the congestion window size and RTT in SSPD and SSPID.

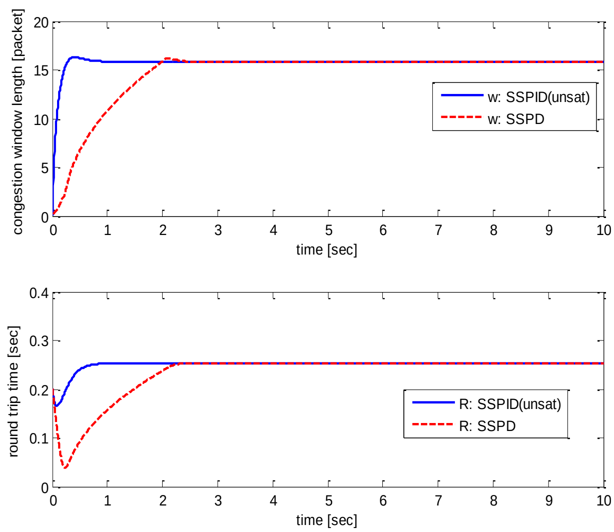

Fig. 3. Congestion window size and RTT in in SSPD and SSPID

The congestion window size in SSPD and SSPID converges to a constant value after a certain period of time which shows the closed-loop system stability. Also, RTT converges to a constant value after the transient time. Fig. 4 shows the sliding surface and its derivative in SSPD and SSPID. It can be seen that the sliding surface and its derivative converge to zero in SSPD. However, the sliding surface in SSPID does not converge to zero.

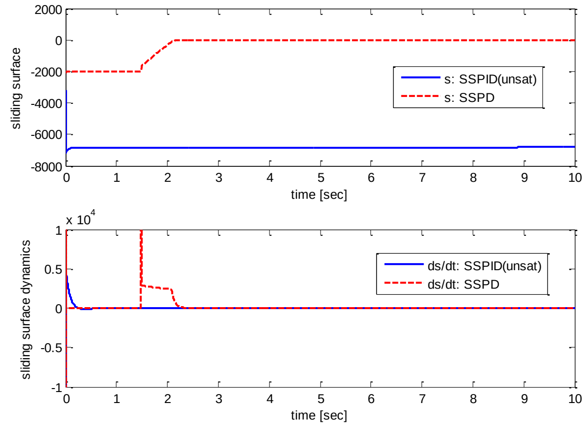

Fig. 4. Sliding surface and its derivative in in SSPD and SSPID

B. Performance Analysis of the Proposed Controllers in the Presence of Disturbance

In this part, the performance of the proposed controller is studied in the presence of disturbance. A step disturbance (value=20, time=10) is applied to the average queue length. Table I shows the performance of the proposed controllers in case of average queue length error, average congestion window size error, average RTT error and average packet drop probability with and without disturbance.

Table I. Performance Of The Proposed Controllers With And Without Disturbance

SSPID (with disturbance)	**SSPID (without disturbance)**	**SSPD (with disturbance)**	**SSPD (without disturbance)**	**Scheme** / **Performance metrics**
6141.8	4910.5	3895.1	3395.3	Average queue length error
6.7812	5.8491	5.6480	5.1880	Average congestion window size error
0.0616	0.0603	0.0596	0.0591	Average RTT error
5.9184×10^{-4}	5.3271×10^{-4}	3.8958×10^{-4}	3.1167×10^{-4}	Average packet drop probability

Table I shows that SSPD without disturbance outperforms SSPD with disturbance in terms of average queue length error, average congestion window size error, average RTT error and average packet drop probability. Also, SSPID without disturbance outperforms SSPID with disturbance in terms of average queue length error, average congestion window size error, average RTT error and average packet drop probability. Moreover, SSPD without disturbance ends in better performance comparing with SSPD with disturbance, and SSPID with/without disturbance. Also, SSPID with disturbance performs the worst comparing with SSPID without disturbance, and SSPD with/without disturbance.

C. Comparison of the Proposed Controller with PI and PID Controllers

In this part, the performance of the proposed controller (SSPD) is compared with PI [21] and PID [22] controllers. In [21], given that W_0, p_0 and q_0 are the equilibrium points of TCP nonlinear system, the transfer function of δp and δq is determined as follows:

$$G_{pq}(s) = \frac{R_0 C_0 K}{\left(R_0 s + \frac{1}{K}\right)(R_0 s + 1)} e^{-R_0 s} \tag{30}$$

where

$$\delta p = p(t) - p_0,\ \delta q = q(t) - q_0,\ K = \frac{R_0 C_0}{2N_0},\ R_0 = T_0 + \frac{q_0}{C_0} \tag{31}$$

In [21], the performance of PI controllers is studied in TCP networks. In this paper, Skogestad's method [23] is suggested where the system transfer function as the following first order approximation is taken into consideration:

$$G_{pq}(s) \approx \frac{R_0 C_0 K^2}{\left(K + \frac{1}{2}\right) R_0 s + 1} e^{-\frac{3}{2} R_0 s} \tag{32}$$

The controller parameters are derived as follows:

$$k_p = \frac{1}{C_0 K^2} \frac{K + 0.5}{\tau_c + 1.5 R_0},$$
$$k_i = \frac{k_p}{\min\{K R_0 + 0.5 R_0, 4(\tau_c + 1.5 R_0)\}} \tag{33}$$

The following values are obtained as the controller parameters:

$k_p = 4.2196,\ k_i = 3.7056$

Based on the model, a PID controller is as follows [22]:

$$G_c(s) = 2.9067 \times 10^{-5} \left(1 + \frac{1}{5.45 s} + 0.4157 s\right) \tag{34}$$

In this section, the desired average queue length is 120. Fig. 5 shows the tracking of the desired queue length in the proposed controller, PI and PID controllers.

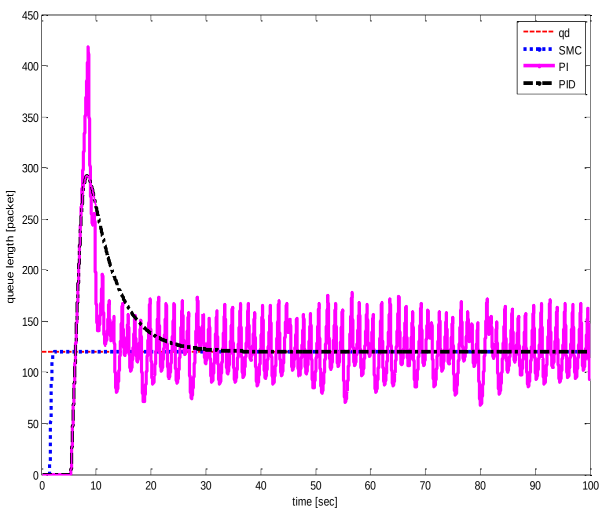

Fig. 5. Tracking of the desired queue length in the proposed controller, PI and PID controllers

Fig. 5 shows that the proposed scheme renders satisfactory tracking of the desired queue length comparing with PI and PID controllers. The PID controller ends in an undesired transient closed-loop response and a very high overshoot. Also, the PI controller renders unsatisfactory performance comparing with the proposed scheme since the desired queue length significantly fluctuates. Fig. 6 shows the packet drop probability in the proposed controller, PI and PID controllers. Also, the congestion window size is shown in Fig. 7.

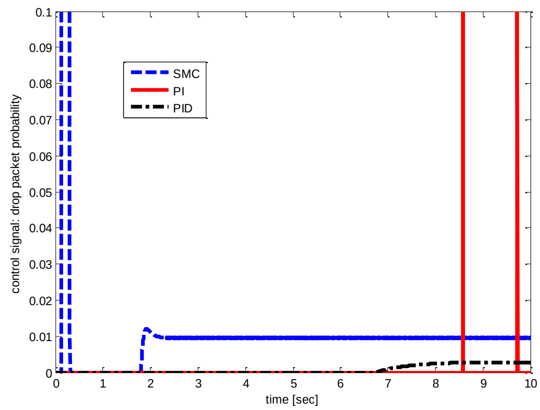

Fig. 6. Packet drop probability in the proposed controller, PI and PID controllers

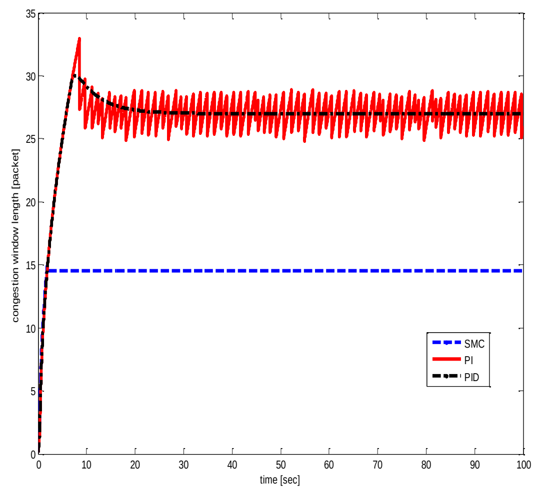

Fig. 7. Congestion window size in the proposed controller, PI and PID controllers

Fig. 6 shows that the PI controller has the worst packet drop probability, however the packet drop probability in the PID controller is less than the proposed controller. Also, Fig. 7 shows that the desired value of congestion window size is gained in the proposed controller, however a fluctuating congestion window size is obtained in the PI controller. So, satisfactory performance is not obtained in the PI controller. Fig. 8 shows the packet round-trip time in the proposed controller, PI and PID controllers.

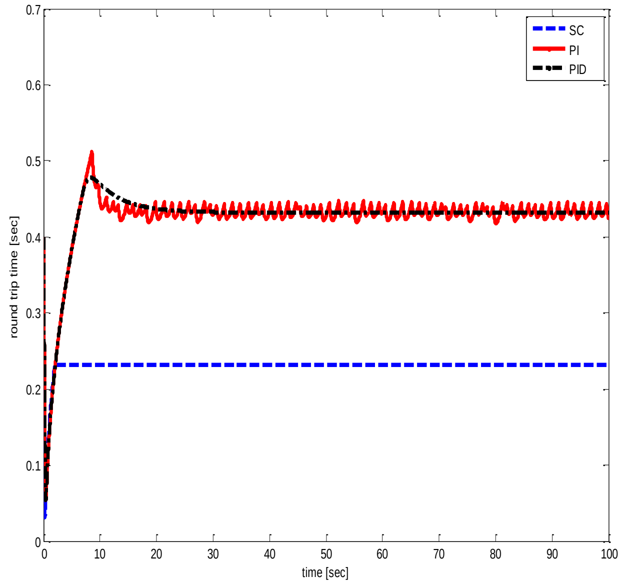

Fig. 8. Packet round-trip time in the proposed controller, PI and PID controllers

The packet round-trip time in the proposed controller is less than that of the PI and PID controllers. The congestion window size in Fig. 7 and RTT in Fig. 8 demonstrate that the proposed method outperforms PI and PID schemes. The performance of the proposed controller, PI and PID controllers are compared in Table II.

TABLE II. Performance of The Proposed Controller, PI And PID Controllers

PI	PID	The proposed controller	Scheme / Performance metrics
5427.2	4160.6	3395.3	Average queue length error
6.2886	5.7190	5.1880	Average congestion window size error
0.0617	0.2360	0.0591	Average RTT error
3.6×10^{-4}	0.594×10^{-4}	3.1167×10^{-4}	Average packet drop probability

Table II demonstrates that the proposed controller outperforms PI and PID controllers. The PI controller has the highest mean queue length error, however, the PID controller outperforms the PI controller with less packet drop probability and less congestion window size. Also, the PID controller has the worst packet round-trip time and the proposed scheme renders the best queue length tracking.

VI. Conclusions

In this study, the sliding mode control scheme is presented for desired queue length tracking in TCP-based computer network. In this regard, the proportional-Integrator-derivative and proportional-derivative sliding surface is defined and the control signal is extracted. Also, the Lyapunov stability conditions are satisfied. The proposed scheme renders satisfactory performance in the presence of disturbance. Also, no chattering occurs in the control signal and satisfactory transient response is gained. The comparison between the proposed method with PI and PID control schemes shows the superiority of sliding mode control comparing with the aforementioned controllers where congestion window size remains unchanged, satisfactory control signal is achieved and less overshoot is obtained.

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