UNDERSTANDING HIGHSPEED TCP: A CONTROL-THEORETIC PERSPECTIVE

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ABSTRACT
One of the most promising solution for transport protocol over very high bandwidth-delay product networks is HighSpeed TCP. However, little is known about its performance as well as its interaction with other elements of the network (such as the RED queue management). In this paper, a comprehensive control-theoretic analysis of HighSpeed TCP is provided. We develop a fluid-flow model of the HighSpeed TCP/RED network and use it to study its performance. The main contributions of this paper are the following. Firstly, we provide a fluid-flow model for HighSpeed TCP/RED networks. Secondly, a comprehensive and *systematic* implementation methodology is described in detail. We also provide a Simulink-based framework for analyzing fluid-based models. Thirdly, we give stability conditions for HighSpeed TCP/RED networks. Finally, the results are validated by simulations using Ns-2 [11].

KEY WORDS
HighSpeed TCP, RED, control theory, performance analysis.

1 Introduction

Recent experience indicates that the congestion control of current TCP prevents it from fully utilize high-speed wide-area connections. Thus, network applications demanding high bandwidth are rarely able to take full advantage of high-speed networks and they are often not utilizing the available bandwidth. The major reason for under utilization is that the additive increase of traditional TCP is too slow and the multiplicative decrease is too harsh.

HighSpeed TCP [1] (among others [2], [3], [4]) is a recently proposed revision to the TCP congestion control mechanism. It is specifically designed for use in networks with high bandwidth-delay product. There exist very few studies on the performance implication of HighSpeed TCP so far [5], [6].

This paper provides a control-theoretic model to estimate the performance of HighSpeed TCP in a very high bandwidth-delay product network environment. The motivation behind our approach is to gain analytical insight into the performance of HighSpeed TCP. Control-theoretic approach proves to be a very promising tool to model the dynamics of traditional TCP/AQM networks (TCP/RED network in particular) [7], [8], [9], [10].

In this paper, a comprehensive control-theoretic analysis of HighSpeed TCP is presented. The main contributions of the paper are the following. Firstly, we provide a fluid-flow model for HighSpeed TCP/RED networks. Secondly, a comprehensive and *systematic* implementation methodology is described in detail. We also provide a Simulink-based framework for analyzing fluid-based models. Thirdly, we give stability conditions for HighSpeed TCP/RED networks. Finally, the results are validated by simulations using Ns-2 [11].

This paper is organized as follows. In Section 2, we summarize the congestion control mechanism of HighSpeed TCP. In Section 3, the fluid-flow model of HighSpeed TCP/RED networks is given. Section 4 describes the Simulink implementation of the model and validates the results based on simulations. In Section 5, a control-theoretic stability analysis for HighSpeed TCP/RED networks is provided. Conclusions are given in Section 6.

2 Congestion control of HighSpeed TCP

The congestion management of TCP is composed of two important algorithms. The Slow-Start and Congestion Avoidance algorithms [12] allow the protocol to increase the data sending rate of sources without overwhelming the network. TCP updates a variable called congestion window ($CWND$) that directly affects the sending rate. From our point of view, the details of Congestion Avoidance phase are relevant. Several models to capture the TCP dynamics have been developed, see e.g. [13], [14].

The Congestion Avoidance phase of regular TCP can be characterized by additive increase and multiplicative decrease (AIMD) which means that the TCP increases the congestion window by one packet per window of data acknowledged and halves the window for every window of data containing a packet drop (or marking).

HighSpeed TCP (HSTCP) was specified in [1] as a modification of TCP's congestion control mechanism to improve performance in case of large congestion windows. HSTCP introduces a new relation between the average congestion window and the steady-state packet drop (or marking) rate. It was designed to have the standard

TCP response in environments with mild to heavy congestion (packet loss rates of at most 10^{-3}) and to have a different, more aggressive response in environments of very low congestion event rate. The modified response function can be characterized by four parameters: Low_Window, $High\_Window$, $High\_P$ and $High\_Decrease$. When $CWND \leq Low\_Window$, then HSTCP uses the same response function as regular TCP, else it uses the more aggressive one. $High\_Window$ and $High\_P$ are used to specify the upper end of the response function. The relation between the response function and the parameters is shown in Figure 1. The response function is plotted in a log-log scale.

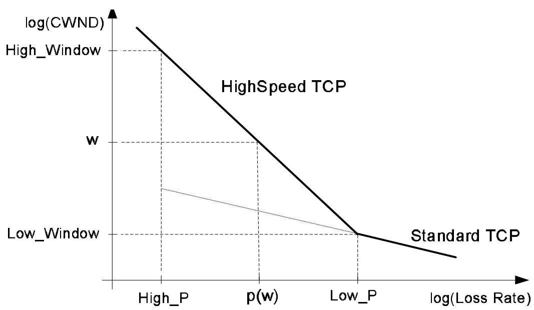


Figure 1. HSTCP response function and its parameters

In Congestion Avoidance, HSTCP applies new additive increase and multiplicative decrease parameters depending on the current congestion window size. The behavior can be expressed as follows:

$$\textbf{ACK} \; : \; CWND \leftarrow CWND + \frac{a(CWND)}{CWND}$$
$$\textbf{DROP} \; : \; CWND \leftarrow CWND - b(CWND) \times CWND$$

where $a(CWND)$ and $b(CWND)$ can be derived from the basic parameters of the protocol (see [1, 5] for more details).

3 Fluid-flow model

Our model is based on the model presented in [7, 8] for TCP-Reno/RED networks. We generalized this model for networks using HighSpeed TCP (HSTCP) protocol. In this section, the basics of the fluid-flow model are summarized.

The examined fluid-model captures the expected (average) transient behavior of a HSTCP/RED network.

We used the following variables:

W	$\doteq$	expected TCP window size (packets),
q	$\doteq$	expected queue length (packets),
x	$\doteq$	expected queue length estimation (packets),
R	$\doteq$	round-trip time (RTT) $= \frac{q}{C} + T_p$ (secs),
C	$\doteq$	link capacity (packets/sec),
T_p	$\doteq$	fix propagation delay (secs),
N	$\doteq$	load factor (number of TCP sessions),
p	$\doteq$	probability of packet mark/drop.

3.1 HighSpeed TCP source model

The dynamics of the congestion window of a HighSpeed TCP source can be described by the following differential equation:

$$\dot{W}(t) = \frac{a(W(t))}{R(t)} - b(W(t))\, W(t) \frac{W(t-R(t))}{R(t-R(t))}\, p(t-R(t)) \tag{1}$$

where the first term corresponds to the additive increase part of the algorithm using the increase parameter $a(W(t))$. This term expresses that the congestion window is increased by $a(W(t))$ packets per one round-trip time. The second term corresponds to the multiplicative decrease part depending on the decrease parameter $b(W(t))$. RED realizes a proportional marking scheme marking packets of flows according to the flows' bandwidth share. Thus, the decrease of the congestion window is weighted by the delayed rate $\frac{W(t-R(t))}{R(t-R(t))}$ and the marking probability $p(t-R(t))$. We emphasize that this differential equation gives an approximation for the expected dynamics of the congestion window.

The main difference between our HSTCP source model and the published TCP-Reno model [7] originates from the fact that the increase and decrease parameters of the HSTCP protocol depend on the current value of congestion window $(W(t))$ which yields a more complicated differential equation than the one for TCP-Reno.

3.2 Network model

Considering a network with one single bottleneck link fed by identical TCP flows, the expected transient behavior of the queue can be captured by the following differential equation:

$$\dot{q}(t) = N(t)\frac{W(t)}{R(t)} - 1_{q(t)}C \tag{2}$$

where the first term reflects the increase of the queue length according to the arrival rate and the second term reflects the decrease part depending on the service rate. $1_{q(t)} = 1$ if $q(t) > 0$, and zero otherwise. There is an AQM (Active Queue Management) policy associated with this router. We focused on the classical RED (Random Early Detection) [15] policy characterized by a packet discard function $p(x)$ taking the average queue length estimation $x(t)$ as its argument. At packet level simulation, e.g. in Ns-2 [11], the average queue length is computed after every packet arrival applied an exponentially weighted moving average. This can be described by a difference equation that can be converted to a differential equation as follows:

$$\dot{x}(t) = Kx(t) + Kq(t) \tag{3}$$

where $K = -C\ln(1-\alpha)$ and α is the forgetting factor. This is a first order low pass filter with a cutoff frequency of K.

The AQM module acting as a controller (using control-theoretic terms) feeds back the congestion measure (marking or dropping probability) to the TCP senders according to its parameters. The TCP sources as parts of the controlled plant adjust their sending rates based on the experienced marking probability. The next step is to capture the dynamics of the congestion window.

The equations (1), (2) and (3) describing the HighSpeed TCP sources and the network dynamics, respectively, form coupled differential equations modeling the HSTCP/RED network. This system of differential equations – having complex dependence between the variables and containing variable delay in some arguments – is analytically not tractable. Thus, we apply numerical approximation to solve these complex equations.

4 Implementation and validation of the model

So far, we did not find detailed explanations about the numerical approximation methods used to solve related differential equations modeling TCP/RED networks. In this section, we illustrate our new, systematic approach to implement the previously presented system of differential equations.

The system described by non-linear differential equations was implemented in the Simulink environment of MATLAB. It includes blocks describing the behavior of each part and we get a clear and tractable framework. The basic elements of the model is presented in Figure 2.

The HSTCP source is modeled by the block called "Cwnd dynamics" which captures the behavior of the HSTCP's congestion window control algorithm. The size of the congestion window W is set according to the packet-marking probability p and the round-trip time R. The marking probability is derived from the instantaneous queue length q by the AQM module, while the current round-trip time is originated from the queue length. The dynamics of the queue length is affected by the current window size, round-trip time and the system load N (number of sources). The input of the system is the load (N_input). The key network variables are saved to MATLAB workspace by the corresponding elements.

4.1 Implementation of HSTCP source model

The building blocks of the subsystem representing the dynamics of HSTCP's congestion window are presented in Figure 3. The increase and decrease parameters are derived by an implemented MATLAB function and affects the additive increase and multiplicative decrease algorithms according to the specification of HighSpeed TCP [1].

4.2 Implementation of network model

The round-trip time module implements a simple correspondence between the queue length and the RTT according to the following equation:

$$R = T_p + \frac{q}{C}. \quad (4)$$

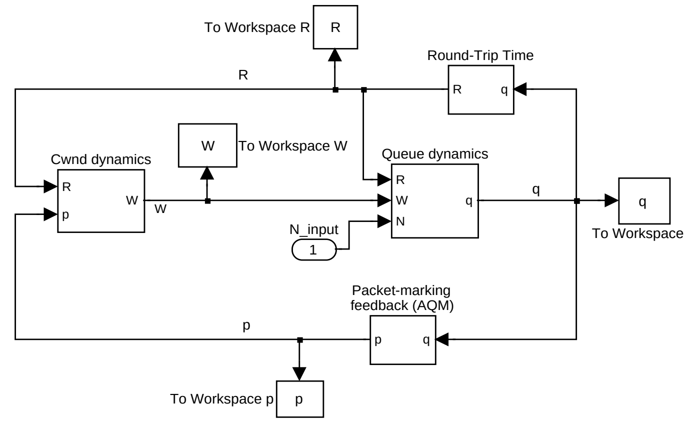


Figure 2. Basic elements of the model (top-level)

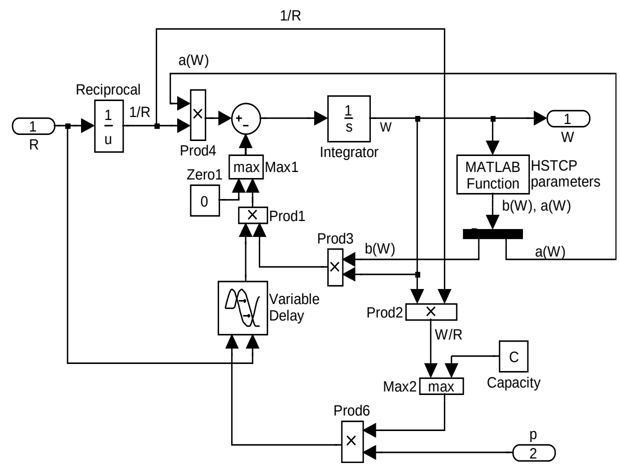


Figure 3. Dynamics of Cwnd - HighSpeed TCP

The module realizing AQM policy consists of a low-pass filter averaging the instantaneous queue length and a marking function associated with the RED marking profile. The output of this subsystem is the packet marking probability p. The basic RED algorithm has three parameters (p_{max}, t_{min}, t_{max}) [15] characterizing the packet marking profile.

The block belonging to the single bottleneck queue dynamics is shown in detail in Figure 4. It realizes the corresponding differential equation (2).

4.3 Validation of the model

The previously introduced model was analyzed using Simulink's imbedded differential equation solver tools with different parameters and was validated by simulations conducted in the well-known Ns-2 [11] environment. In this section, the main results of this analysis are presented.

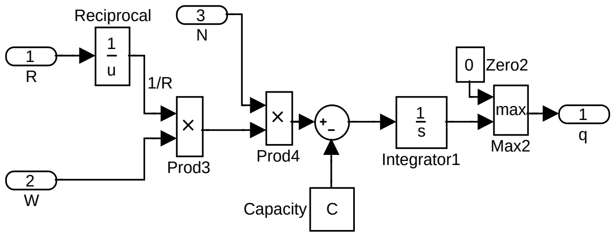


Figure 4. Queue dynamics

During our investigation, we used the "ode45" differential equation solver implementing the Domand-Prince algorithm (numeric approximation). The investigated network scenario contained identical TCP flows feeding a single queue belonging to the bottleneck link. The basic behavior of the model was examined with one TCP flow. The parameters of HighSpeed TCP and the parameters of RED (packet-marking profile) are summarized in Table 1.

We examined a link characterized by high bandwidth-delay product, namely the link bandwidth was $1\,Gbps$, the packet size was $1500\,bytes$ and the propagation delay was $100\,ms$.

Table 1. Parameters

HSTCP parameters

Low_Window	38
$High\_Window$	$8,300$
$High\_P$	10^{-6}
$High\_Decrease$	0.1

RED parameters

p_max	0.01
t_min	$4,000$
t_max	$8,000$

The results of a simple single flow scenario are presented as an example. We compare the congestion window of Simulink flow simulation (model) with Ns-2 simulation in Figure 5. Since we only consider the Congestion Avoidance phase, we show only the steady-state results.

The dynamics of instantaneous queue length can also be validated in the same way. The outcome of the model and the simulation are shown in Figure 6.

The results indicate that the analytic model is capable of accurately capturing the behavior of HighSpeed TCP and queue dynamics.

5 Stability analysis

In control-system language, the RED module can be referred as the controller or compensator and the rest of the system as the plant. The objective of the controller design is to provide a stable and robust closed-loop system with acceptable transient response. A similar stability analysis was carried out for HSTCP/RED networks as it was published in [8] for TCP-Reno sources.

First, we linearize the non-linear fluid-flow model (presented in Section 3) about an equilibrium point. Then

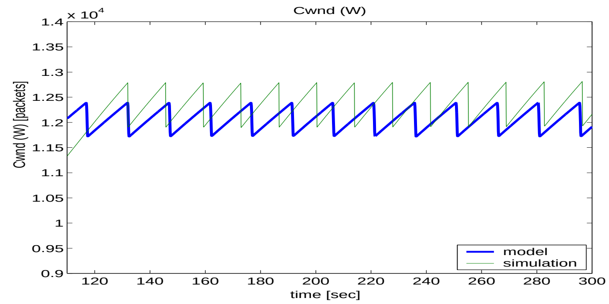


Figure 5. Dynamics of the Cwnd

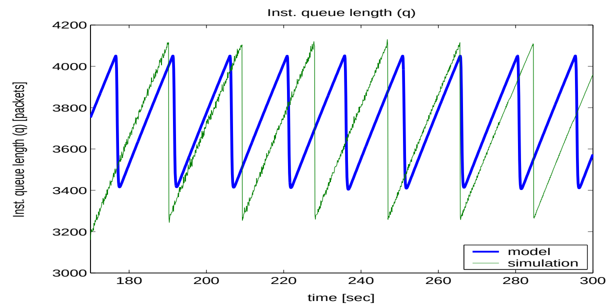


Figure 6. Dynamics of the instantaneous queue length

we give a condition for RED parameters to stabilize the linear feedback control system for a given range of parameters. Finally, we analyze the stability margins of the system and give a lower bound for phase margin and gain margin, respectively.

5.1 Linearization of the model

The plant – including HSTCP sources and bottleneck queue – is modeled by differential equations (1), (2). Taking W and q as state variables and p as input of the plant, the operating point (W_0, q_0, p_0) is given by $\dot{W} = 0$ and $\dot{q} = 0$. Using small-signal linearization, we assume that load factor and round-trip delay are constants:

$$N(t) \equiv N \quad \text{and} \quad R(t) \equiv R_0 = \frac{q_0}{C} + T_p.$$

Moreover, the increase and decrease parameters of HSTCP can be considered similarly:

$$a(W(t)) \equiv a(W_0) = a_0 \quad \text{and} \quad b(W(t)) \equiv b(W_0) = b_0.$$

a_0 and b_0 can be derived directly from the basic parameters (Low_Window, $High\_Window$, $High\_P$ and $High\_Decrease$) of HSTCP (see [1] for more details):

$$b(W_0) = \frac{(High\_Dec - 0.5) \times (\log W_0 - \log Low\_W)}{\log High\_W - \log Low\_W} + 0.5$$

$$a(W_0) = \frac{W_0^2 \times p(W_0) \times 2 \times b(W_0)}{2 - b(W_0)} \tag{5}$$

where

$$
\begin{aligned}
p(W_0) &= \exp\left\{\frac{\log W_0 - \log Low\_W}{\log High\_W - \log Low\_W}\cdot\right. \\
&\qquad \left.(\log High\_P - \log Low\_P) + \log Low\_P\right\} \\
Low\_P &= \frac{1.5}{Low\_W^2}.
\end{aligned}
$$

Substituting zero for $\dot{W}$ and $\dot{q}$, the following equations can be derived for the operating point:

$$W_0^2 p_0 = \frac{a_0}{b_0} \quad \text{and} \quad W_0 = \frac{R_0 C}{N}. \tag{6}$$

Taking the partial derivatives of the right hand side of equation (1) and (2), we linearize the system about the operating point:

$$
\begin{aligned}
\delta\dot{W}(t) &= -\frac{a_0 N}{R_0^2 C}\left(\delta W(t) + \delta W(t - R_0)\right) \\
&\quad -\frac{b_0 R_0 C^2}{N^2}\delta p(t - R_0) \\
\delta\dot{q}(t) &= \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t)
\end{aligned} \tag{7}
$$

where the variables denote perturbations ($\delta W \doteq W - W_0$, $\delta q \doteq q - q_0$ and $\delta p \doteq p - p_0$).

This linear system can be transformed into the Laplace transform domain and the transfer function can be derived:

$$
\begin{aligned}
P(s) &= -e^{-sR_0}\, P_{hstcp}(s)\; P_{queue}(s) = \\
&= -e^{-sR_0}\, \frac{\frac{b_0 R_0 C^2}{N^2}}{s + \frac{a_0 N}{R_0^2 C}\left(1 + e^{-sR_0}\right)}\; \frac{\frac{N}{R_0}}{s + \frac{1}{R_0}}
\end{aligned} \tag{8}
$$

where the first term e^{-sR_0} corresponds to a delay of R_0 and $P_{hstcp}(s)$ and $P_{queue}(s)$ describe the behavior of HSTCP and the queue, respectively. The delay term (e^{-sR_0}) that appears in the denominator of the transfer function $P_{hstcp}(s)$ can be eliminated by a similar approximation as it was used in [8]. The subtle difference to be taken into consideration is the changed condition that makes the approximation acceptable. For regular TCP, this condition requires that $W_0 \gg 1$. In our case, the new requirement

$$W_0 \gg a_0 \tag{9}$$

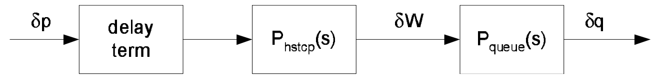
is also a reasonable assumption for typical network conditions.

Thus, we get a simplified linear model as it is shown by the block diagram in Figure 7.

Remarks:

1. The negative eigenvalues of HSTCP and queue dynamics $(-\frac{2a_0 N}{R_0^2 C}, -\frac{1}{R_0})$ indicate that the equilibrium state of the non-linear dynamics is locally asymptotically stable.

2. If we substitute the increase and decrease parameters of HSTCP $a_0 = 1$ and $b_0 = 0.5$ we get the linear model of the network with regular TCP-Reno sources.



$$P_{hstcp}(s) = \frac{\frac{b_0 R_0 C^2}{N^2}}{s + \frac{2a_0 N}{R_0^2 C}} \quad ; \quad P_{queue}(s) = \frac{\frac{N}{R_0}}{s + \frac{1}{R_0}}$$

Figure 7. The simplified linear model

5.2 Designing RED for HighSpeed TCP

The previously presented plant – including the HSTCP sources and the bottleneck queue – and the RED controller form a feedback control system. The transfer function of the RED controller can be modeled in a range of queue length as follows [8]:

$$C(s) = C_{red}(s) = \frac{L}{\frac{s}{K} + 1} \tag{10}$$

where

$$L = \frac{p_{max}}{t_{max} - t_{min}} \quad \text{and} \quad K = -\frac{\ln(1-\alpha)}{\delta},$$

α is the queue averaging parameter (or forgetting factor) and δ is the sample time [7]. L is the slope of the curve characterizing the RED marking profile, whereas K is the cutoff frequency of the RED controller.

The objective of our RED design for a network with HSTCP sources is to select RED parameters L_{hstcp} ($= \frac{p_{max}}{t_{max} - t_{min}}$) and K_{hstcp} to stabilize the feedback control system for a given range of N and R_0. That range can be defined as follows:

$$N \ge N^- \quad \text{and} \quad R_0 \le R^+.$$

For the sake of clarity, we summarize the used parameters:

L_{hstcp}, K_{hstcp}	:	RED-based control system parameters (explained above)
a_0, b_0	:	HSTCP increase/decrease parameters at the operating point
C	:	Capacity of the link
N^-	:	Minimum number of flows
R^+	:	Maximum value of the RTT

Proposition 1 (Stability condition) *If L_{hstcp} and K_{hstcp} satisfy*

$$\frac{L_{hstcp}\, b_0\, (R^+ C)^3}{2a_0\, (N^-)^2} \le \sqrt{\frac{\omega_g^2}{K_{hstcp}^2} + 1} \tag{11}$$

where

$$\omega_g = 0.1 \min\left\{\frac{2a_0 N^-}{(R^+)^2 C}, \frac{1}{R^+}\right\} \tag{12}$$

then, the linear feedback control system showed in Figure 8 is stable for all $N \ge N^-$ and $R_0 \le R^+$.

This condition gives a stability region for the HSTCP/RED network. Set of parameters within that region gives stable system.

Proof: The frequency response function of the loop transfer function is

$$L(j\omega) = \frac{L_{hstcp} \frac{b_0 (R_0 C)^3}{2a_0 N^2} e^{-j\omega R_0}}{\left(\frac{j\omega}{K_{hstcp}} + 1\right)\left(\frac{j\omega}{\frac{2a_0 N}{R_0^2 C}} + 1\right)\left(\frac{j\omega}{\frac{1}{R_0}} + 1\right)}.$$

The goal of this controller design is to force the RED module ($C_{red}(s)$) to dominate closed-loop behavior which is achieved by making the closed-loop time constant ($\approx 1/\omega_g$) greater than the maximum of the other two time-constants $\left(\frac{(R^+)^2 C}{2a_0 N^-},\ R^+\right)$ of the transfer function. Thus, the following approximation can be applied

$$L(j\omega) \approx \frac{L_{hstcp} \frac{b_0 (R_0 C)^3}{2a_0 N^2} e^{-j\omega R_0}}{\frac{j\omega}{K_{hstcp}} + 1} \quad \text{for} \quad \forall \omega \in [0, \omega_g].$$

For a given range of N and R_0 we get an upper bound for the gain at ω_g:

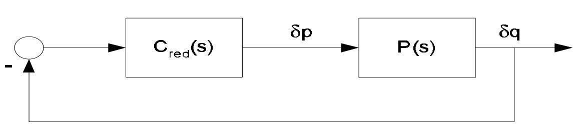
$$|L(j\omega)| \leq \frac{L_{hstcp} \frac{b_0 \left(R^+ C\right)^3}{2a_0 (N^-)^2}}{\sqrt{\frac{\omega_g^2}{K_{hstcp}^2} + 1}}.$$

From this and (11) it follows that $|L(j\omega_g)| \leq 1$ for all $N \geq N^-$, $R_0 \leq R^+$. Thus, the crossover frequency ω_c (where $L(j\omega_c) = 1$) is bounded above by ω_g which yields that

$$\angle L(j\omega_c) \geq \angle L(j\omega_g) = \angle \frac{L_{hstcp} \frac{b_0 (R_0 C)^3}{2a_0 N^2}}{\frac{j\omega_g}{K_{hstcp}} + 1} - \omega_g R_0 \geq$$
$$\geq -90^\circ - 0.1 \frac{180^\circ}{\pi} > -180^\circ$$

where we used the condition (12). We get that $\angle L(j\omega_c) \geq -180^\circ$ indicating the stability based on Nyquist stability criterion. ■

Remarks: It is important to note that if we substitute the increase and decrease parameters of HSTCP $a_0 = 1$ and $b_0 = 0.5$ in (11) and (12) we get the conditions for the network with regular TCP-Reno sources [8].



$$P(s) = \frac{\frac{b_0 C^2}{N} e^{-sR_0}}{\left(s + \frac{2a_0 N}{R_0^2 C}\right)\left(s + \frac{1}{R_0}\right)} \quad ; \quad C_{red}(s) = \frac{L_{hstcp}}{\frac{s}{K_{hstcp}} + 1}$$

Figure 8. Block diagram of the linearized feedback control system

5.3 Experimental results

This section is devoted to the presentation of some experimental results.

Based on the derived stability condition (Proposition 1) for HSTCP/RED networks, a stability region can be defined. Taking Equations (11) and (12), the RED parameter L_{hstcp} can be expressed in the terms of N^- and R^+. Assuming that some parameters are constant with typical values (i.e. $K_{hstcp} = 1$, $a_0 = 7.2516$, $b_0 = 0.1$, $C = 83,333$), the stability region can be plotted in 3D. In Figure 9, the values of L_{hstcp} below the plotted surface give stable system according to Proposition 1.

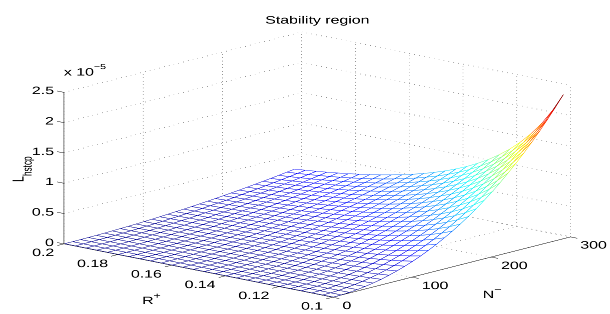


Figure 9. Stability region

As an illustration, two different scenarios with single bottleneck link are examined and the results of the fluid-flow model and Ns-2 simulations are compared. The basic parameters were the same as it was presented in Table 1, furthermore, the link bandwidth was $1\,Gbps$, the packet size was $1500\,bytes$ and the propagation delay was $100\,ms$. The RED parameters were the following: $K_{hstcp} = 1$, $L_{hstcp} = 2.5 \cdot 10^{-6}$. The only differing parameter was the number of flows.

Firstly, a parameter set was chosen that yields an unstable system. The number of identical HSTCP flows feeding the same queue belonging to the single bottleneck link was $N = 150$. The instantaneous queue length derived from the model and the simulation are shown in Figure 10. The steady-state characteristics of the queue dynamics and the oscillation are well captured by the model, however, the transient behavior shows difference. Secondly, a scenario was chosen with $N = 300$ which gives a stable system. According to the stability condition, the limit of the stable behavior can be observed at $N = 282$. The instantaneous queue length derived from the model and the simulation are shown in Figure 11. The steady-state characteristics are well captured by the model and the stability can also be observed. However, the transient behavior shows difference in this case, too.

6 Conclusion

In this paper, a control-theoretic analysis of HighSpeed TCP/RED network has been carried out. We have proposed

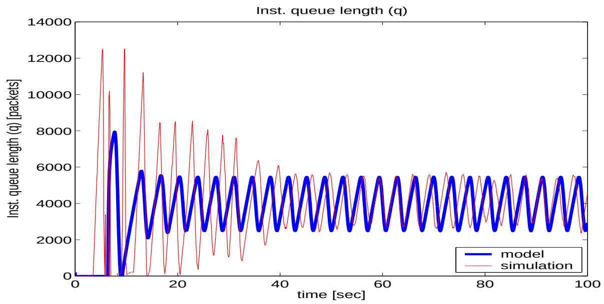


Figure 10. Queue dynamics – unstable system (150 flows)

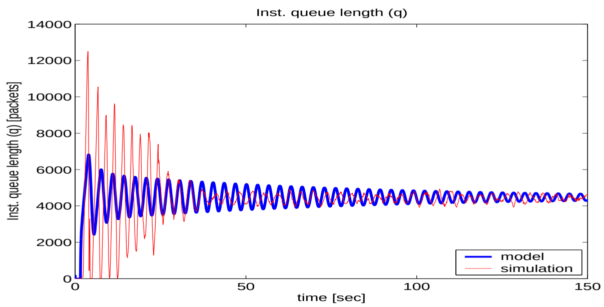


Figure 11. Queue dynamics – stable system (300 flows)

a fluid-flow model for HighSpeed TCP and investigated its performance in a very high bandwidth-delay product network with RED active queue management at the router. We have described in detail a systematic Simulink-based framework for analyzing the dynamics of the HighSpeed TCP/RED network. Based on the model we have derived the stability conditions for HighSpeed TCP network regulated by RED queueing mechanism at the router. The model as well as results are validated through simulations by using Ns-2.

Our analysis raises the issue but it leaves many questions unaddressed. In the future, we plan to extend the current model to study other high speed variants of TCP, such as Scalable TCP, FAST TCP and XCP. We also plan to use model to study fairness issues of these protocols in a very high bandwidth-delay product network environment.

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