ON STABILITY CONDITIONS FOR HIGH-SPEED VARIANTS OF TCP AND RED BASED AQM

AUN HAIDER, HARSHA SIRISENA, VICTOR SREERAM, AND RICHARD HARRIS

Abstract. This paper investigates the stability of Active Queue Management (AQM) system formed by high-speed variants of Transmission Control Protocol (TCP) and Random Early Detection (RED) routers. Dynamical modeling is used to analyze the stability of the closed loop system at the operating point in terms of the number of high-speed TCP connections. It has been shown that periodic doubling bifurcations can occur by varying the system parameters. Two conditions for designing a stable high-speed TCP-RED system for a high capacity Gigabit network are also derived. Finally, Lyapunov Exponents and Bifurcation diagrams have been employed to investigate the dynamical behaviour of AQM systems.

Key Words. High-speed variants of standard TCP, RED, AQM, and Stability.

1. Introduction

The current best-effort Internet has been ubiquitously used around the world. Its successful operation mainly depends upon the use of TCP for data transfer between end hosts, i.e. data sender and receiver. It has predominantly deployed two versions of TCP, Reno and Sack, which have been evolving in the last two decades. TCP over Internet Protocol (IP) provides necessary stability and robustness to the current Internet. The operation of TCP depends on four intertwined algorithms: slow start, congestion avoidance, fast retransmit and fast recovery, [1]. Whereas, amount of data pumped into network is mainly controlled by congestion avoidance algorithm, [1] and [2].

A number of intermediate routers are usually involved in establishing and maintaining TCP connection(s) between sender(s) and receiver(s) of data. The simplest possible type of a router is Droptail, which starts to drops the incoming packets after its receive buffer has become completely full. However, a significant problem associated with Droptail is flow synchronization [3]. Also, it cannot support Quality-of-Service applications such as in DiffServ architectures, see [4] and its references. Therefore, in order to overcome weaknesses of Droptail and efficiently utilize the network resources, Random Early Detection RED was proposed in [3]. A RED router while working in conjunction with TCP, can form a closed loop feedback system, that is widely known as Active Queue Management (AQM). At the onset of congestion, an AQM control loop can perform dropping or marking of packets as congestion signals to data sender(s). Whereof receiving the proactively marked acknowledgement packet the sender will decrease the congestion window (a TCP variable that controls the the number of data packets that can be send into the network for transmission).
Recently, due to major advancements in router hardware and fiber optical based data transmission link technologies, there has been a wide spread trend of upgrading of existing as well as deployment of new high-speed networks, e.g. [5], [6], [7] and [8]. These high-speeds networks are being used for various data intensive applications, such as High Energy/Nuclear Physics, Bio-Informatics and Telemedicine, [10]. These networks need to transfer a huge amount of data over Gigabit links for which the performance of ordinary standard TCP is not satisfactory. For instance, a standard TCP connection will take 1.5 hours to fully utilize a 10 Gb/s link, [11]; which is highly time consuming and thus undesirable. Therefore, in order to efficiently utilize the available bandwidth, new data transfer protocols are required.

Towards this end, in about the last seven years, several variants of TCP for high-speed networks have been proposed in literature. These proposals can be classified into following three categories: (i) pure packet loss based, such as HighSpeed TCP [11], Scalable TCP [12] and Binary Increase Congestion Control (BIC) [13] (ii) delay based approaches such as Fast TCP [14] (iii) combination of loss and delay, such as Compound TCP [15]. This paper only considers loss and loss-delay combination approaches for high-speed TCP, as pure delay based congestion control has severe problems in fair sharing of bandwidth with loss based algorithms, [15]. It extends our previous work by generalizing the modelling and analysis of stability conditions derived for Scalable TCP-RED based AQM, [9]. The basic notation and model used in this paper was originally proposed in [16] in the context of standard TCP, which has also been used in [17] for the bifurcation analysis of AQM formed by standard TCP and RED router.

The rest of the paper is organised as follows: dynamics of congestion control for standard and high-speed variants of TCP are presented in Section 2. A discrete time model of high-speed TCP-RED is developed in Section 3. The conditions for stability are derived in Section 4. Case studies are provided in Section 5. Finally, conclusions and future work are presented in Section 6.

2. Dynamics of congestion control

2.1. Standard TCP. The operation of congestion avoidance algorithm in standard TCP can be summarized in the following two steps [1]:

- For each acknowledgement packet, update the congestion window \( W_r \), as
  \[
  W_r \leftarrow W_r + a_r \cdot W_r
  \]
- For packet drop/mark, update \( W_r \) as \( W_r \leftarrow W_r - b_r \cdot W_r \) and for acknowledgements during slow start \( W_r \leftarrow W_r + c_r \);

where \( a_r = 1, b_r = 0.5 \) and \( c_r = 1 \); with all quantities expressed in maximum segment size (packets). It is also known as additive-increase multiplicative-decrease of the congestion window. A typical congestion window plot for a standard TCP connection, operating in the congestion avoidance phase, is shown in Fig. 1. By using a sawtooth series, as shown in Fig. 1, the congestion window, \( W_r \), and throughput (amount of data transferred successfully), \( T_r \) (Packets/s), for packet drop/mark probability of \( p \) and round trip time \( R \), has been derived in [18] as:

\[
W_r = \sqrt{\frac{2a_r}{b_r(2-b_r)}} \cdot \frac{1}{p},
\]

\[
T_r = \frac{\sqrt{a_r(2-b_r)}}{R\sqrt{2b_r}} \equiv \frac{\sqrt{1.5}}{R\sqrt{p}}.
\]

(1)

(2)
2.2. High-speed variants of TCP. In order to obtain a generalized expression for stability of high-speed variants of TCP, synchronised packet loss model has been employed [13]. In this model all high-speed TCP connections, competing for bottleneck link bandwidth, simultaneously experience the loss events. Thus, each high-speed TCP connection with different round trip time will experience a different loss rate. It is in contrast to uniformly distributed packet loss model, where all connections regardless to their round trip times will obtain same packet loss rate. In general, throughput of high-speed variants of standard TCP, with synchronized loss model, can be elegantly expressed as [13]:

$$T_h = \frac{1}{R} \cdot \frac{K_h}{\rho^d},$$

where $K_h$ and $d$ are constants whose value depend upon the type of high-speed TCP, as has been summarized in Table 1. Both (3) and (2) give throughput in

<table>
<thead>
<tr>
<th>Type of high-speed TCP</th>
<th>$K_h$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard TCP [1]</td>
<td>1.22</td>
<td>0.5</td>
</tr>
<tr>
<td>Scalable TCP [12]</td>
<td>0.08</td>
<td>1</td>
</tr>
<tr>
<td>HighSpeed TCP [11]</td>
<td>0.15</td>
<td>0.82</td>
</tr>
<tr>
<td>BIC TCP [13]</td>
<td>-</td>
<td>[0.5, 1]</td>
</tr>
<tr>
<td>Compound TCP [15]</td>
<td>-</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 1. Values of $K_h$ and $d$ for TCP variants for high-speed networks.

Packets/s, which can be converted into bits/s by multiplying them with maximum segment (Packet) size $M$ (bits). A snapshot of variations in congestion window and a plot of response function, equation (3), for major types of high-speed TCPs have been shown in Fig. 2 and 3 respectively.
3. Discrete time Model for High-Speed TCP-RED System

Let us consider the feedback control loop formed by high-speed TCP and a RED router, as shown in Fig. 4. In order to describe the behavior of this closed loop system, we consider discrete time intervals, $t_{k+1} = t_k + R$, where $R$ consists of a propagation delay and queuing delay. The packet mark/drop probability in any given time slot, $t_k$, is $p_k$. On receiving the congestion signal (through marked/dropped packets), the sender reduces its congestion window. Thus, variations of the queue at the RED router are governed by $q_{t_{k+1}} = q_{k+1} = G(p_k)$. RED computes a new estimate of exponential weighted moving average, $\bar{q}_{e,k+1}$, of the instantaneous queue size $q_{k+1}$, i.e. $\bar{q}_{e,k+1} = A(\bar{q}_{e,k}, q_{k+1})$. After computing $\bar{q}_{e,k+1}$, RED computes a
new value of $p_{k+1}$ as $p_{k+1} = H(\bar{q}_{e,k+1})$. Therefore, we have the following set of equations to describe the closed loop shown in Fig. 4:

\[
q_{k+1} = G(p_k), \\
\bar{q}_{e,k+1} = A(\bar{q}_{e,k}, q_{k+1}), \\
p_{k+1} = H(\bar{q}_{e,k+1}).
\]

For a link capacity of $C$ (bits/s), maximum queue size (buffer capacity) of $B$ (packets), fixed number of connections $N$ and packet size $M$, the following idealized queue law for high-speed TCP, modified from that proposed in [16] for standard TCP, is as follows:

\[
q_{k+1} = G(p_k) \equiv \begin{cases} 
\max \left( B, \frac{C}{M} \left( \frac{MK_h}{p_k} - R_0 \right) \right), & \text{for } p_k \leq p_0; \\
0, & \text{otherwise};
\end{cases}
\]

(4)

where, $p_0$ is maximum value of probability for which link capacity is fully utilized and $R_0$ is the corresponding round trip time. The physical interpretation of this equation is that, assuming the buffer capacity $B$ is not exceeded, the number of packets in the buffer is equal to the window size less the number of packets in-flight, i.e. the product of the networks capacity in packets/s times the round-trip time.

In a real system (with time varying $N$, $M$ and $R_0$), for the maximum values of $N$, $M$ and minimum value of $R_0$, (5) is called “maximum queue law”; whereas for the minimum values of $N$, $M$ and maximum value of $R_0$ it is called “minimum queue law”, [16]. However, the actual queue law can be in between the minimum and maximum values. The behavior of a RED router, i.e. $p_{k+1} = H(\bar{q}_{e,k+1})$, can be described by the following:

\[
p_{k+1} = \begin{cases} 
0, & \text{if } \bar{q}_{e,k+1} < q_{\text{min}}; \\
1, & \text{if } \bar{q}_{e,k+1} \geq q_{\text{max}}; \\
\frac{q_{\text{max}} - q_{\text{min}}}{p_{\text{max}}}, & \text{if } \bar{q}_{e,k+1} \in [q_{\text{min}}, q_{\text{max}}],
\end{cases}
\]

(6)

where average of queue size variations, $\bar{q}_{e,k+1}$, is computed by following recursion:

\[
\bar{q}_{e,k+1} = A(\bar{q}_{e,k}, q_{k+1}) \equiv (1 - w)\bar{q}_{e,k} + w \cdot q_{k+1},
\]

(7)
where \( w \) is queue averaging weight, whose value can be set as, e.g., in [3] and [21]. Also, we have \( 0 < p_{\text{max}} < 1 \) and the following heuristic, [3]:

\[
q_{\text{max}} - q_{\text{min}} = 2q_{\text{min}}.
\]  

Thus, the system formulated in (4) has been completely described by (5), (6) and (7). For large buffer \( B \), we can write (5) as:

\[
q_{k+1} = \frac{C}{M} \left\{ \frac{MK_h}{C/N \cdot \bar{p}_e^d} - R_0 \right\}.
\]  

Substituting (9) in (7) we get:

\[
\bar{q}_{e,k+1} = (1 - w)\bar{q}_{e,k} + w \cdot \left\{ \frac{N K_h}{p_{\text{max}}(\bar{q}_{e,k} - q_{\text{min}})} \right\}^d - \frac{R_0 C}{M}.
\]  

Next, plugging (6) in (10) results in:

\[
\bar{q}_{e,k+1} = (1 - w)\bar{q}_{e,k} + w \left[ N K_h \cdot \frac{q_{\text{max}} - q_{\text{min}}}{p_{\text{max}}(\bar{q}_{e,k} - q_{\text{min}})} \right]^d - \frac{R_0 C}{M}.
\]  

Simplifying (11) we have:

\[
\bar{q}_{e,k+1} = \bar{q}_{e,k} + w \left[ N K_h \cdot \frac{q_{\text{max}} - q_{\text{min}}}{p_{\text{max}}(\bar{q}_{e,k} - q_{\text{min}})} \right]^d - \frac{R_0 C}{M}.
\]  

The “equilibrium value” or “fixed point” in (12) occurs when \( \bar{q}_{e,k+1} = \bar{q}_{e,k} \equiv \bar{q}^* \), [17], giving the following condition:

\[
N K_h \cdot \left( \frac{q_{\text{max}} - q_{\text{min}}}{p_{\text{max}}} \right)^d = (\bar{q}^* + \frac{R_0 C}{M}) (\bar{q}^* - q_{\text{min}})^d,
\]  

where \( 0.5 \leq d \leq 1 \). In the case \( d = 0.5 \), i.e. standard TCP, we will have the following expression:

\[
(\bar{q}^* - q_{\text{min}}) \left( \frac{R_0 C}{M} - q_{\text{min}} \right) = (\frac{N K_h}{p_{\text{max}}})^2 (q_{\text{max}} - q_{\text{min}})
\]

For \( d = 1 \), i.e. Scalable TCP case, we can have:

\[
\bar{q}^* + \bar{q}^* \left( \frac{R_0 C}{M} - q_{\text{min}} \right) - \left\{ \frac{R_0 C q_{\text{min}}}{M} + \frac{N K_s}{p_{\text{max}}} \cdot (q_{\text{max}} - q_{\text{min}}) \right\},
\]

which is in contrast to the cubic equation derived in [17], for the standard TCP-RED case. After substituting (8) in (15), an expression for \( \bar{q}^* \) can be obtained as:

\[
\bar{q}^* = \frac{1}{2} \left( \frac{R_0 C}{M} - q_{\text{min}} \right) + \frac{1}{2} \sqrt{\left( \frac{R_0 C}{M} - q_{\text{min}} \right)^2 - 4 \left\{ \frac{R_0 C q_{\text{min}}}{M} + \frac{N K_s}{p_{\text{max}}} \cdot (q_{\text{max}} - q_{\text{min}}) \right\}},
\]

where the positive square root is selected on the RHS of (16) because \( \bar{q}^* > 0 \).

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1For further insight, expressions for \( (\bar{q}^* - q_{\text{min}})^2 \) can be obtained through (16); i.e. assuming \( k_1 = \frac{R_0 C}{M} \) and \( k_2 = \frac{N K_s}{p_{\text{max}}} \) we can have:

\[
(k_1 + k_2)^2 = \frac{1}{2} \left( k_1 + q_{\text{min}} \right) + \frac{1}{2} \sqrt{(k_1 - q_{\text{min}})^2 - 4 q_{\text{min}} (k_1 + K_2)},
\]

which can be further manipulated, by using binomial expansion, as:

\[
(\bar{q}^* - q_{\text{min}})^2 = \frac{k_1^2}{4} - q_{\text{min}} (k_1 + K_2) (1 + K_1 + q_{\text{min}}),
\]

for positive root in (16);

\[
q_{\text{min}} (k_1 + K_2) (1 + k_1 + q_{\text{min}}),
\]

for negative root in (16);
4. Stability Analysis

Stability of high-speed TCP-RED system, (4), can be analyzed by linearizing (11) at the fixed point \( \bar{q}^* \) and determining the eigenvalue, [17]:

\[
\frac{\partial \tilde{q} \text{, } e,k+1}{\partial \tilde{q} \text{, } e,k} \bigg|_{q_e,k=\bar{q}^*} = 1 - w - \left( \frac{q_{\text{max}} - q_{\text{min}}}{p_{\text{max}}} \right)^d \frac{wNdK_h}{(\bar{q} \text{, } e,k - q_{\text{min}})^{d+1}},
\]

which after substitution of (8) can be written as:

\[
\frac{\partial \tilde{q} \text{, } e,k+1}{\partial \tilde{q} \text{, } e,k} \bigg|_{q_e,k=\bar{q}^*} = 1 - w - \left( \frac{2q_{\text{min}}}{p_{\text{max}}} \right)^d \frac{wNdK_h}{(\bar{q} \text{, } e,k - q_{\text{min}})^{d+1}}.
\]

The eigenvalue given by (20) depends upon the fixed point \( \bar{q}^* \) as defined by (15).

In order that (4) be stable, the eigenvalue must lie inside the unit circle, giving the following condition for stability:

\[
1 - w - \left( \frac{2q_{\text{min}}}{p_{\text{max}}} \right)^d \frac{wNdK_h}{(\bar{q} \text{, } e,k - q_{\text{min}})^{d+1}} < 1.
\]

There will be a period doubling bifurcation with oscillations when the eigenvalue, (19), becomes equal to -1, [17]. The value of the queue weight, \( w \), for which eigenvalue equals -1 is given by:

\[
w_{\text{crit}} = \frac{2}{1 + \left( \frac{2q_{\text{min}}}{p_{\text{max}}} \right)^d \frac{wNdK_h}{(\bar{q} \text{, } e,k - q_{\text{min}})^{d+1}}}
\]

To analyze the nature of bifurcations we consider a function \( S \) as defined in [22]:

\[
S = \frac{1}{2} \left( \frac{\partial^2 \tilde{q} \text{, } e,k+1}{\partial \bar{q} \text{, } e,k^2} \right)^2 + \frac{1}{3} \left( \frac{\partial^3 \tilde{q} \text{, } e,k+1}{\partial \bar{q} \text{, } e,k^3} \right).
\]

Taking second and third order derivatives in (11) we get:

\[
\frac{\partial^2 \tilde{q} \text{, } e,k+1}{\partial \bar{q} \text{, } e,k^2} \bigg|_{q_e,k=\bar{q}^*} = \left( \frac{2q_{\text{min}}}{p_{\text{max}}} \right)^d \frac{wNd(d+1)K_h}{(\bar{q} \text{, } e,k - q_{\text{min}})^{d+2}}.
\]

\[
\frac{\partial^3 \tilde{q} \text{, } e,k+1}{\partial \bar{q} \text{, } e,k^3} \bigg|_{q_e,k=\bar{q}^*} = \left( \frac{2q_{\text{min}}}{p_{\text{max}}} \right)^d \frac{wNd(d+1)(d+2)K_h}{(\bar{q} \text{, } e,k - q_{\text{min}})^{d+3}}.
\]

Substituting (24) and (25) in (23) we obtain:

\[
S = \frac{1}{2} \left( \frac{\partial^2 \tilde{q} \text{, } e,k+1}{\partial \bar{q} \text{, } e,k^2} \right)^2 + \frac{1}{3} \left( \frac{\partial^3 \tilde{q} \text{, } e,k+1}{\partial \bar{q} \text{, } e,k^3} \right).
\]

A positive value of \( S \) indicates that the bifurcation is supercritical, whereas a negative value indicates subcritical region which represents discontinuity and is not desired. The first term in (26) will be always positive. Thus, for \( S > 0 \) we can have:

\[
\left\{ \frac{2NK_hwq_{\text{min}}}{(\bar{q}^* - q_{\text{min}})^2} - 1 \right\} > 0,
\]

which gives the following condition:

\[
(\bar{q} \text{, } e,k - q_{\text{min}}) < \left( \frac{3q_{\text{min}}}{2p_{\text{max}}} \frac{wNd(d+1)K_h}{d+2} \right)^{\frac{1}{d+1}}
\]

that can be substituted in (22) for \( d = 1 \), to obtain \( w_{\text{crit}} \) independent of \( \bar{q}^* \).
In a real network scenario with non-adaptive RED [3], each of $K_s$, $w$, $q_{\text{min}}$ and $p_{\text{max}}$ is a constant, whereas the number of high-speed TCP connections vary with time, i.e. $N = N(t_k) \equiv N_k$. Hence, we can write (28) as:

$$ N > \frac{2p_{\text{max}}(\bar{q}_{e,k} - q_{\text{min}})^d}{3q_{\text{min}} wd(d+1)K_h} $$

where $\bar{q}^*$ is an implicit function of filter weight $w$ via (15). To summarize, in order that AQM comprising high-speed TCP and RED be stable, both (21) and (29) must be satisfied.

5. Case Studies

In order to further investigate the behavior of dynamical system defined by (10), we employ Lyapunov Exponents (LEs), [22] pp. 283. They determine the exponential rates at which the nearby trajectories deviate from each other with time. Consider two initial conditions $x_0$ and $x_0 + \delta x_0$ for a dynamical system defined by $f(x)$, which map to $x_1$ and $x_1 + \delta x_1$; i.e. in general $x_{n-1} + \delta x_{n-1}$ mapping to $x_n + \delta x_n$, respectively. Thus, we can have

$$ \delta x_n = f'(x_{n-1})\delta x_{n-1}, $$

which can be further written as

$$ \left| \frac{\delta x_n}{\delta x_0} \right| = \prod_{i=0}^{n-1} |f'(x_i)|. $$

Assuming that (31) varies exponentially at for large values of $n$, we have:

$$ |\delta x_n| = e^{\lambda_L n}, $$

where $\lambda_L$ is called Lyapunov Exponent, which is given by the following expression:

$$ \lambda_L = \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} \ln |f'(x_i)|. $$

$\lambda_L < 0$ indicates stable fixed point or stable periodic orbit for a non-conservative system having asymptotic stability. The superstable fixed points and periodic orbits have $\lambda_L = -\infty$. $\lambda_L = 0$ is a neutral fixed point for a conservative system having Lyapunov stability. $\lambda_L > 0$ indicates instability and chaos, see [22] and http://hypertextbook.com/chaos/43.shtml

5.1. High-Speed Variants of TCP. We consider a system deploying high-speed variants of TCP and RED router, as depicted in Fig. 5, and analyze its stability characteristics by using LEs and Bifurcation diagrams. In this setup we have chosen $q_{\text{min}} = 500$, $q_{\text{max}} = 1500$ packets, $p_{\text{max}} = 0.1$, bottleneck link capacity $C = 2.4$ Gbps, round trip time of 0.1 s, number of connections $N = 10$ and maximum packet size of 4000 bytes, [20].

![Figure 5. Dumbbell Network Topology.](image-url)
LEs for HighSpeed, Scalable, and Compound TCP-RED have been computed by solving (33) with Mathematica package. For instance, the LEs for Compound TCP for different values of $R_0 C/M$ have been shown in Fig. 6. It has been observed that for each type of high-speed TCP-RED system the LEs have almost similar shape characteristics and these plots are always positive for $0 < w < 1$; thus corresponding to system that has a stable fixed point or stable periodic orbits.

It also shows that high-speed TCP-RED based system is more stable for higher values of $w$. It corroborate the results presented for TCP-RED in [23], which suggests that $0.5 < w < 1$ for smoother queue variations and reduced jitter (latency in packet arrival) for the buffered packets. A bifurcation diagram is also often used to investigate the behaviour of a dynamical system. It indicates the qualitative changes in the nature and number of fixed points of a system whose parameters are being varied quasistatically. The horizontal axis shows the parameter being varied and vertical axis indicates the measure of steady states (equilibria/fixed points). The bifurcation diagrams, for various values of round trip time, for different high-speed TCPs have been plotted in Fig. 7. It has been found that high-speed TCP-RED based AQM start to show the bifurcation behaviour for $R \in [0.01 \text{ms}, 1 \text{ms}]$ and the plot tends to move toward the vertical axis for smaller values of $R$. Further, for comparison and completion purpose, we have also studied the case of standard TCP-RED based AQM.

5.2. TCP Reno/SACK. Consider the case of ordinary TCP employing RED in a dumbbell topology, as in Fig. 5, with $q_{\text{min}} = 250$, $q_{\text{max}} = 750$ packets, $p_{\text{max}} = 0.1$, bottleneck link capacity $C = 75$ Mbps, round trip time of 0.1 s, number of connections $N = 250$ and maximum packet size of 4000 bytes, [17]. Using (33), the LEs are computed and plotted in Fig. 8(a). Next, in order to compare with the high-speed TCP-RED system, we set $q_{\text{min}} = 500$, $q_{\text{max}} = 1500$ packets and $N = 10$ (with other parameters same) and plot LEs in Fig. 8(b). These plots show that LEs for ordinary TCP-RED based system become positive for certain range of values of

![Figure 6. LEs for Compound TCP [15].](image-url)
Figure 7. Bifurcation plots for various high-speed TCP-RED based AQMs for $R_0$=1, 0.1 and 0.01 ms: (a), (b) and (c) for High-Speed TCP [11]; (d), (e) and (f) for Scalable TCP [12]; (g), (h) and (i) for Compound TCP [15], respectively.
queue weight $w$, thus causing instability. However, a high-speed TCP-RED based system avoids such behaviour. Also, in contrast to high-speed TCP, bifurcation behaviour can be observed for higher values of round trip time.

6. Conclusions and Future work

The dynamical behaviour of AQM formed by high-speed TCP-RED has been analyzed by developing a discrete time nonlinear model. A generalized equation describing the behaviour of the fixed point has been developed. Special case for Scalable TCP has been also analyzed. Further, two conditions for designing stable high-speed TCP-RED based AQM have been derived. The stability of ordinary TCP and high-speed TCPs with RED routers has been investigated by using Lyapunov Exponents and Bifurcation diagrams. It has been shown that ordinary TCP-RED based systems are less stable than high-speed TCP-RED. Also, it has been found that high-speed TCP-RED systems are more stable for higher values of queue weight, $w$; a fact which has also been pointed out for ordinary TCP-RED systems in [23].

Further, we plan to carry out packet level simulations on high-speed TCP-RED system to further investigate the stability conditions and also corroborate the inferences drawn from Lyapunov Exponents and bifurcation plots as presented in this paper.

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