Available online at www.elixirpublishers.com (Elixir International Journal)

Network Engineering

Elixir Network Engg. 90 (2016) 37473-37489

Elixir ISSN: 2229-712X

Performance analysis and enhancement of TCP using Normalised Delay Gradient (NDG) in wireless networks

N.G.Goudru[1,*] and B.P.Vijaya Kumar[2]

[1]Department of Mathematics, BMS Institute of Technology (affiliated to VTU), Bangalore, India.

[2]Department of Information Science and Engineering, MS Ramaiah Institute of Technology (affiliated to VTU), Bangalore, India.

ARTICLE INFO

Article history:

Received: 28 November 2015;

Received in revised form: 30 December 2015;

Accepted: 5 January 2016;

Keywords

Convergence,
Immediate-Recovery,
NDG,
Loss-predictor,
Stability,
Oscillatory,
Transmission loss,
Wireless loss.

ABSTRACT

In this paper, we consider a new method to improve the performance of TCP over wireless networks. The method employs NDG loss-predictor function to determine congestion losses from that of transmission loss. The sender window can adjust its size depending on the loss information. If the loss is due to congestion, congestion control algorithm is invoked to decrease the flow rate. If the loss is due to wireless transmission, immediate-recovery algorithm is invoked to recover from the losses caused by the sender TCP. To minimise the packet losses due to congestion, we use stability analysis over the system by applying a time-delay control theory. By constructing Hermite matrix, system analysis is made for asymptotic stability. Explicit conditions are derived for P_{max} (RED controller) and β (f_{NDG} parameter) in terms of wireless network parameters. Using the characteristic equation of the Hermite matrix, convergence analysis of the instantaneous queue length at the bottleneck router is made. Convergence of the queue length to a given target value is analysed. This minimises the oscillatory behaviour of the RED router. An approximate solution of queue length is also derived. Our results provide better solutions for global stability and convergence conditions of the wireless system.

Introduction

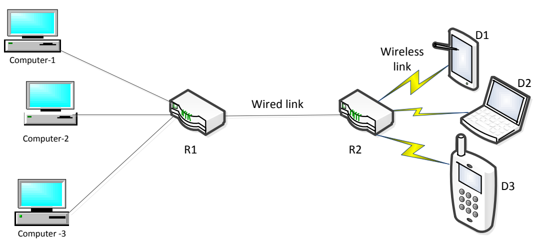

Figure 1. Network model

Because of advancement in 3G, 4G and 5G technologies, Communication network has evolved exponentially. TCP (Transmission control protocol) an important transport layer protocol suite used extensively in data transport applications. About 90% of the Internet traffic is carried by TCP. TCP provide an end-to-end connection oriented packet transport mechanism that ensures the reliable and ordered delivery of data. TCP needs to perform not only in wired network but it should also evolve to meet the challenges introduced by the wireless part of the network. TCP was originally designed for the wired networks. In wired networks, random bit error rate (BER) is negligible and Packet losses due BER can be ignored. The TCP sender properties works fairly well in wired networks. In wireless networks, high BER cannot be a negligible factor for packet losses. TCP's congestion control (CC) and congestion avoidance (CA) mechanism based on the assumption that all packet losses due to congestion fail in handling the transmission losses. TCP without modification exhibit throughput degradation when traverses wireless link. To improve the performance of TCP over wireless link, the researchers proposed many techniques. Some of them are, I-TCP (Indirect TCP)- In the base station two different channels are used, one link is wired to connect wired host to base station and the second link is wireless, to connect from base station to mobile station. After receiving the data from source, base station transmits data to the mobile station as if it is transmitting using wired link [4]. M-TCP (Mobile TCP) has the facility of keeping a retransmission timer in the base station. This timer is used by the sender TCP for checking the time-out period. For each receive of the data packet, base station sends an acknowledgement packet to the source before the timer period expires [5]. SNOOP is data link layer assisted protocol used to improve the performance of TCP in wireless environment. The base station keeps track of all the packets transmitted from a source TCP. Base station keeps a copy of the packet in its buffer till it receives the acknowledgement. It removes the packet from its buffer after acknowledgement is received. When a packet loss occurs because of wireless

Tele: 90-9341384414

E-mail addresses: nggoudru@gmail.com

transmission error, base station retransmits the lost packet. SOONP protocol does not answer for time-out event occurrence in mobile wireless transmission or the duplicate acknowledgements [6]. ELN (Explicit Loss Notification) keeps the wireless loss information in the base station, and the base station sets the ELN bit to the duplicate acknowledgement. For the ELN-set duplicate acknowledgement, source TCP assumes that the packet loss is due to wireless transmission error and does not decrease its window size which results in congestion [7]. W-TCP (Wireless-TCP) is a rate-based wireless congestion control protocol. W-TCP assumes that the packet losses due to burst traffic as router congestion and random losses as the wireless transmission error. In each case, the receiver measures the time interval of the received packets and communicates the source to control the sending rate by using this time interval estimate [8]. TCP Westwood is a sender-side modification for wireless TCP. From the acknowledgement packet received, the sender estimates the current sending rate. For the congestion notification, the sender decides the congestion window size from the estimated sending rate. TCP Westwood has problem in time estimation and needs a fine-grained timer. In a dynamically changing network, the estimation cannot be accurate [9]. The ACK Pacing algorithm can be used for black-out and hand-off delays. By sending ACK Pacing packets, burst data delivery is prevented from old path and the route update for new path [10]. JTCP (Jitter-based) JTCP method is for heterogeneous wireless networks to adopt sending rates to the packet losses and jitter ratios [11]. ACK-Splitting improves the TCP throughput over wired and wireless heterogeneous networks [12]. However, these schemes may not have good performance or fairness or it is too complex to deploy in wireless systems. To satisfy these challenges and for applying TCP over wireless link, we propose a model based scheme that can dynamically change the sending rate to the packet loss due to congestion and transmission. The model has been integrated with the capability of distinguishing the packet losses due to congestion or transmission. If the loss is due to congestion, congestion control algorithm is invoked to reduce the network congestion and when the loss is due to transmission, immediate-recovery algorithm is invoked to recover from the decreased flow rate. One of the popular congestion avoidance schemes called RED (random early detection) and an accurate loss-predictor function called NDG loss-predictor which is designed based on CAT are used in the system model. Congestion avoidance technique (CAT) monitors the level of congestion in the network, and instructs the source that the sender window should be increased or decreased and vice versa. A TCP source understands that a particular packet has lost due to congestion or due to wireless transmission error and take appropriate action [18]. To enhance performance of TCP for further, we apply stability [13, 14]. A time-delay control theory is used and Hermite matrix method is applied to analyse the asymptotic stability. A relationship between RED parameter p_{max} and NDG loss-predictor parameter β is established. The stability boundaries are established in terms of wireless network parameters. The work is further enhanced by analysing the queue convergence at the ingress point of the bottleneck link. Using characteristic equation of the Hermite matrix, an approximate solution for the instantaneous queue length, q(t) is derived. The convergence boundaries of q_0, p_{max} and β are presented. Using these boundary values, convergence analysis of the queue length for a given target value is discussed. This helps in maintaining RED router stable. Using Matlab numerical results are given to validate the analytical results. The above illustrated characteristics collectively make TCP robust by minimising the packet losses and maximising throughput. Our results provide global stability and convergence conditions of the system.

System Model for Wireless Networks

The extended fluid model [15, 16, 17, 21] that describe the dynamics of the TCP congestion window size in wireless networks is,

$$dW(t) = \frac{dt}{RTT} - \alpha\, W(t)\, L_a(t) + \beta L_t(t) \tag{1}$$

TCP operates on AIMD congestion avoidance strategy. The factor α is decrease rate of source window which is normally 0.5, L_a (t) is the rate of arrival of packet losses due to congestion at time t and $L_a(t) = \frac{w(t-R(t))}{R(t-R(t))}\, p(t - R(t - R(t)))$. This loss is proportional to the throughput at the source. First term on the right hand side of equation (1) refers to exponential increase of the sender window size until congestion occurs at the destination. The second term refers to congestion avoidance scheme based on RED. The third term L_t(t) refers to immediate-recovery due to transmission loss. The transmission loss is proportional to the sending rate of the source. Therefore, L_t (t) is proportional to $\frac{w(t-R(t))}{R(t-R(t))}$.

The equation (1) can be modified to,

$$\frac{\partial w}{\partial t} = \frac{1}{R(t)} - \frac{w(t)w\big(t-R(t)\big)}{2R\big(t-R(t)\big)}\, p\big(t-R(t)\big) + \beta\, \frac{w\big(t-R(t)\big)}{R\big(t-R(t)\big)} \tag{2}$$

β is called NTG loss-predictor parameter. It has some constant rate of transmission-loss and by choice β ϵ[0,1]. The differential version of Lindley's equation for capturing the dynamic behaviour of instantaneous queue length is given by,

$$\frac{\partial q(t)}{\partial t} = \frac{N\, w(t)}{R(t)} - C_d \tag{3}$$

Where, w(t)/R(t) is increase in queue length due to arrival of the packets from N-TCP flows. The down-link capacity, C_d = q(t)/R(t) is the decreasing factor in queue length due to servicing of the packets and delay of the packet departure from the router. The service time is variable. One of the most important advantages of using instantaneous queue length over average queue length is faster detection of congestion. The mathematical version of RED scheme for dropping packets with probability is given by,

$$P(t) = \begin{cases} 0\ , & q(t) \in [0, t_{min}] \\ \dfrac{q(t) - t_{min}}{W_{max} - t_{min}} P_{max}\ , & q(t) \in [t_{min}, W_{max}] \\ 1\ , & q(t) \geq W_{max} \end{cases} \quad (4)$$

Congestion loss is assumed to take place when queue buffer of the router reaches a value of W_{max} packets. The maximum buffer size, W_{max} of the router is given by,

$W_{max} = \frac{C_d}{S} R(t) + M$, Where C_d/S is the bandwidth delay product, M (in packets) is the buffer size of the router, R(t) is the round trip time. The buffer overflow takes place when the congestion window size becomes larger than W_{max} value. C_d is the down-link bandwidth. The model describing round trip time (RTT) in wireless networks is given by,

$R(t) = \frac{q(t)}{C_d} + T_p$, Tp is the propagation delay in the wireless media, $q(t)/C_d$ models the queuing delay.

Normalised Delay Gradient (NDG) as Loss- Predictor

Based on R. Jain [17], Saad Biaz and Nitin Vaidya [18], and David A. Hayes and Armitage [22],

Let, R (round-trip delay(rtt-delay)) and T (throughput) are functions of the w (congestion window). To determine the Knee (the point at which throughput starts increasing), measure R and the gradient, $\frac{dR}{dw}$ of the delay window-curve. To make the congestion avoidance feasible, adjust (increase or decrease) the window size. To determine the correct direction of the window adjustment, we use normalised delay gradient (NDG) given by, NDG = $\frac{\frac{dR}{dw}}{\frac{R}{w}}$. Let P_i be the i^{th} monitored packet. When acknowledgement of i^{th} monitored packet is received then the normal delay gradient function (f_{NDG}) is given by, $f_{NDG} = \frac{(RTT_i - RTT_{i-1})}{(RTT_i + RTT_{i-1})} \frac{(W_i + W_{i-1})}{(W_i - W_{i-1})}$

If load is low, NDG is low. If load is high, NDG is high. Thus, by computing (f_{NDG}), we may be able to decide whether the next packet loss is due to congestion or transmission. Based on that information whether to increase or decrease the sender window size. When acknowledgement is received for a monitored packet Pi, sender TCP calculates the quantity of NDG loss-predictor value (f_{NDG}).

i) If $f_{NDG} > 0$, the next packet loss is due to congestion.

ii)if $f_{NDG} \leq 0$, the next packet loss is due to wireless transmission errors.

The sender TCP use the loss predictor to recognise a particular packet was lost due to congestion or due to wireless transmission errors. The loss predictor NDG is a congestion avoidance technique.

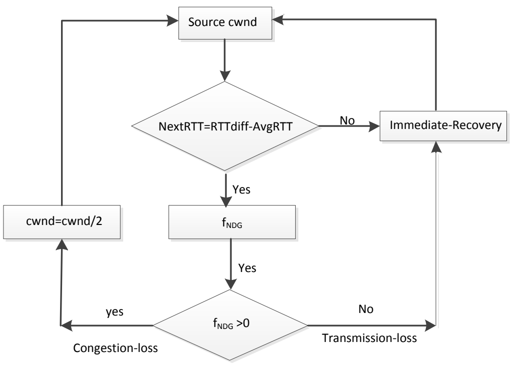

Fig. 2

Figure 2. NDG loss-predictor.

Implementation of the loss predictor in simulation cycle

If ($f_{NDG} > 0$) % congestion loss.
$\beta = 0$ % invoke congestion control algorithm.
end
If ($f_{NDG} \leq 0$) % Wireless transmission error.
$\beta = 0.1$ % invoke Immediate-recovery algorithm.
end

When the source detect that loss is due congestion, NDG parameter, β=0. The threshold value of sender window is fixed to half of the current window size and slow start phase started. When source detects that loss is due to wireless transmission, a loss recovery module called Immediate-recovery algorithm is invoked, where sender window size is added with β-times the sending rate in the previous RTT.

Time-Delay Eedback Control System

In this section, we study the asymptotic stability of TCP in wireless network system. The aim is to save the network system from congestion, and decrease the packet losses accruing due to congestion. The implement methodology involves (i) linearizing the system models, (ii) using the Hermite matrix for time-delay control system, explicit conditions under which the system is asymptotically stability are obtained. A relationship between RED parameter P_{max} and NDG parameter β is derived. The stability regions for P_{max} and β in terms of wireless TCP parameters are obtained.

Linear model derivation

Let x(t) be a general non-linear function defined by, $x(t) = f(u(t), v(t), t)$, where, u(t) represents the sender window dynamics, and v(t) represent the queue dynamics at the bottleneck link. Assuming that $f(u(t), v(t), t)$ has smooth and continuous derivatives around the equilibrium point, $Q_0 = (w_0, R_0, q_0, p_0)$. Using Taylor's series expansion, the linear function of non-linear function, ignoring second and higher order partial derivatives is,

$$f(u(t), v(t), t) = f(u_0(t), v_0(t), t_0) + f_u(t)\delta_u(t) + f_v(t)\delta_v(t) + O(\delta_u(t), \delta_v(t))$$

where $(t) = \frac{\partial f}{\partial u}|(u_0, v_0)$, $f_v(t) = \frac{\partial f}{\partial v}|(u_0, v_0)$. The linear models of the equations (2) to (4) are derived around the equilibrium point $Q_0 = (w_0, R_0, q_0, p_0)$. Let N be the number of TCP flows and R be the round trip time which are considered as constants. At the equilibrium point Q_0, the steady state conditions of equations (2) and (3) are given by

$\dot{w}(t) = 0, \dot{q}(t) = 0$. The estimation algorithm is based on small signal behaviour dynamics, therefore, at the equilibrium point, without loss of generality, we can assume,

$$w(t) = w(t - R(t)) = w_0, q(t) = q(t - R(t)) = q_0, p(t) = p(t - R(t)) = p_0,$$

$$R(t) = R(t - R(t)) = R_0 \tag{5}$$

Using equations (5) in $\dot{w}(t) = 0, \dot{q}(t) = 0$, and after simplification we get,

$$p_0 = \frac{2\beta w_0 + 2}{w_0^2}, w_0 = \frac{R_0 C_d}{N}, N = \frac{R_0 C_d}{w_0}$$

Let, $w_R = w(t - R(t))$, $p_R = p(t - R(t))$. From (2) we get,

$$u(w, w_R, q, p_R) = \frac{1}{R(t)} - \frac{w(t) w_R(t)}{2R(t)} p(t - R(t)) + \beta \frac{w_R(t)}{R(t)} \tag{6}$$

To linearize equation (6), find all the partial derivatives of $u(w, w_R, q, p_R)$ with respect to the variables at the equilibrium point and defining,

$$\delta w(t) = w(t) - w_0, \delta q(t) = q(t) - q_0, \delta p(t) = p(t) - p0$$

$$\delta \dot{w}(t) = \dot{w}(t) - w_0, \quad \delta \dot{q}(t) = \dot{q}(t) - q_0$$

$\delta p(t) = \frac{L}{B}(q(t) - t_{min}) - p_0$, where $B = W_{max} - t_{min}$, $L = p_{max}$

$$\dot{w}(t) = -\left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d}\right)\delta w - \frac{C_d^2 R_0}{2N^2} \delta p_R \tag{7}$$

$$\delta \dot{q}(t) = \frac{N}{R_0}\delta w(t) - \frac{1}{R_0}\delta q(t) \tag{8}$$

$$\delta p(t - R_0) = \frac{L}{B}(\delta q(t - R_0)) + \frac{L}{B}(q_0 - t_{min}) - p_0 \tag{9}$$

Using equation (9) in (7), we get

$$\delta \dot{w}(t) = -\left(\frac{R_0}{w_0} + \frac{2N}{R_0^2 C_d}\right)\delta w(t) - \frac{LC_d^2 R_0}{2N^2 B}\delta q(t - R_0) + \frac{LC_d^2 R_0}{2N^2 B}(t_{min} - q_0) + \frac{R_0 C_d^2 p_0}{2N^2} \tag{10}$$

Denote, $x(t) = \begin{bmatrix} \delta w(t) \\ \delta q(t) \end{bmatrix}$, then

$$\dot{x}(t) = Ax(t) + Ex(t - R(t)) + F \tag{11}$$

Where,

$$A = \begin{bmatrix} -\left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d}\right) & 0 \\ \frac{N}{R_0} & \frac{-1}{R_0} \end{bmatrix} \quad E = \begin{bmatrix} 0 & \frac{-LR_0 C_d^2}{2N^2 B} \\ 0 & 0 \end{bmatrix}, F = \begin{bmatrix} \frac{-LR_0 C_d^2}{2N^2 B}(t_{min} - q_0) + \frac{R_0 C_d^2 p_0}{2N^2} \\ 0 \end{bmatrix}$$

Solving linear differential equation (11) using Laplace transform technique with L{x(t)} = x(s), we get

$$(sI - A - Ee^{-R_0 s})x(s) = \frac{F}{s} \tag{12}$$

The characteristic equation of (12) is, $|sI - A - Ee^{-R_0 s}| = 0$ (13)

After simplification,

$$s^2 + \left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0}\right)s + \left(\frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d} + \frac{LC_d^2}{2NB}e^{-R_0 s}\right) = 0 \tag{14}$$

The characteristic equation (14) determines the stability of the closed-loop time-delay wireless system in terms of the state variables $\delta w(t)$ and $\delta q(t)$.

Stability analysis

Denote, $P(s, e^{-R_0 s}) = s^2 + \left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0}\right)s + \left(\frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d} + \frac{LC_d^2}{2NB}e^{-R_0 s}\right)$

Let $e^{-R0s} = z$, and $a_0 = 1, a_1 = \frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0}, a_2 = \frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d} + \frac{LC_d^2}{2NB}e^{-R_0 s}$

$$P(s, z) = a_0 s^2 + a_1 s + a_2 \tag{15}$$

The Hermit matrix for time-delay control system of equation (15) is

$$H = \begin{bmatrix} (0,1) & (0,2) \\ (0,2) & (1,2) \end{bmatrix}$$

$$(0,1) = 2a_0 a_1 = \frac{2(\beta+1)}{R_0} + \frac{4N}{R_0^2 C_d}$$

$$(0,2) = -2a_2\, Im(z) = \frac{-LC_d^4}{NB} Im(z)$$

$$(1,2) = 2a_1 Re(a_2) = 2\left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0}\right)\left(\frac{\beta}{R_0^2} + \frac{2N}{R_0^3\, C_d} + \frac{LC_d^4}{2NB}\right)$$

Put, $x_1 = \frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0}, x_2 = \frac{LC_d^4}{NB}, x_3 = \frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d}$

Let, $z = e^{i\omega},\ z = cos\omega + isin\omega,\ Re(z) = cos\omega, Im(z) = sin\omega$, then

$$H(e^{i\omega}) = \begin{bmatrix} 2x_1 & -x_2\, sin\omega \\ -x_2\, sin\omega & 2x_1(x_3 + \frac{x_2}{2} cos\omega) \end{bmatrix}$$

Derivation of Stability conditions

The time-delayed control system (2) to (4) is asymptotically stable in terms of stable variables δw(t) and δq(t), if and only if the following two conditions are satisfied.

Condition 1

The Hermit matrix $H(1) = H(e^{i0})$ is positive.

$$H(1) = \begin{bmatrix} 2x_1 & 0 \\ 0 & 2x_1(x_3 + \frac{x_2}{2}) \end{bmatrix}$$

From the determinant, $4x_1^2\left(x_3 + \frac{x_2}{2}\right) > 0$, after simplification,

$$L = p_{max} > -\left(\frac{2\beta NB}{R_0^2 C_d^2} + \frac{4N^4 B}{R_0^3 C_d^3}\right)$$

$$\beta > -\left(\frac{p_{max}\, C_d^4\, R_0^4}{2NB} + \frac{2N}{R_0\, C_d}\right)$$

Condition 2

For all $\omega \epsilon [0,2\pi]$, det $H(e^{i\omega}) > 0$, leads to the following inequality.

$$(2x_1)\left(2x_1\left(x_3 + \frac{x_2}{2}\right)\right) cos\omega - x_2^2 sin^2\omega > 0$$

$$H(e^{i\omega}) = x_2^2 cos^2\omega + 2x_1^2 x_2 cos\omega + 4x_1^2 x_3 - x_2^2 > 0 \quad (16)$$

The necessary condition for (16) to be true is the discriminate, $\Delta > 0$

$$cos\omega = \frac{-x_1^2 \pm \sqrt{x_1^2(x_1^2 - 4x_3) + x_2^2}}{x_2}$$

By the properties of cosine function, for $\omega \epsilon [0,2\pi], cos\omega\ \epsilon[-1, 1]$

The conditions can be written as,

$$\frac{-x_1^2 - \sqrt{x_1^2(x_1^2 - 4x_3) + x_2^2}}{x_2} > 1 \quad (17)$$

$$\frac{-x_1^2 + \sqrt{x_1^2(x_1^2 - 4x_3) + x_2^2}}{x_2} < -1 \quad (18)$$

By direct manipulation, there is no solution for the inequality (17). From (18), we obtain

$$0 < p_{max} < \left(\frac{2\beta NB}{R_0^2 C_d^2} + \frac{4N^4 B}{R_0^3 C_d^3}\right) \quad (19)$$

$$0 < \beta < \left(\frac{p_{max}\ C_d^4\, R_0^4}{2NB} + \frac{2N}{R_0\, C_d}\right) \quad (20)$$

Theorem 1

Given the wireless network parameters C_d (down link capacity), C_u (up link capacity), N (number of TCP sessions), R_0, and the RED parameter B (minimum minus maximum threshold values), the wireless network system given by (2) to (4) is asymptotically stable in terms of the state variables δw(t) and δq(t) if and only if the RED control parameters P_{max} (maximum packet discarding probability) and β (NTG loss-predictor parameter) satisfies,

$$0 < p_{max} < \left(\frac{2\beta NB}{R_0^2 C_d^2} + \frac{4N^4 B}{R_0^3 C_d^3}\right)$$

$$0 < \beta < \left(\frac{p_{max} C_d^4 R_0^4}{2NB} + \frac{2N}{R_0 C_d}\right)$$

Convergence Analysis of Dynamic Queue

In this section, we discussion the of convergence of the buffer queue length in the router. From equation (12),

$$x(s) = (s\,I - A - E\,e^{-R_0 s})^{-1}\,\frac{F}{s} \tag{21}$$

$$(s\,I - A - E\,e^{-R_0 s})^{-1} = \frac{1}{P(s, e^{-R_0 s})}\begin{bmatrix} y_1 & y_2 \\ y_3 & y_4 \end{bmatrix}$$

Where, $y_1 = s + \frac{1}{R_0}$, $y_2 = -\frac{LR_0 C_d^2}{2N^2 B}\,e^{-R_0 s}$, $y_3 = \frac{N}{R_0}$, $y_4 = s + \frac{\beta}{R0} + \frac{2N}{R_0^2 C_d}$

Equation (21) can be written as

$$x(s) = \frac{F}{s\,p(s, e^{-R0s})}\begin{bmatrix} y_1 & y_2 \\ y_3 & y_4 \end{bmatrix}$$

After simplification, $x(s) = \frac{y_5}{s\,p(e^{-R_0 s})}\begin{bmatrix} y_1 \\ y_3 \end{bmatrix}$,

Or $\begin{bmatrix} \delta W(s) \\ \delta Q(s) \end{bmatrix} = y_5 \begin{bmatrix} y_1 \\ y_3 \end{bmatrix}$ (22)

Where,

$$y_5 = \frac{LR_0 C_d^2\ \frac{(t_{min} - q_0)}{2N^2 B} + \frac{R_0 C_d^2 p_0}{2N^2}}{s\,p(s, e^{-R_0 s})}$$

From equation (22),

$$\delta Q(s) = \frac{\frac{N}{R_0}\left(\frac{LR_0 C_d^2}{2N^2 B}(t_{min} - q_0) + \frac{R_0 C_d^2 p_0}{2N^2}\right)}{sP(s, e^{-R_0 s})}$$

$$\delta Q(s) = \frac{\left(\frac{C_d^2}{2N}\right)\left(\frac{L}{B}(t_{min} - q_0) + p_0\right)}{sp(s, e^{-R_0 s})}$$

$$\delta Q(s) = \frac{\frac{1}{s}\frac{C_d^2}{2N}\left(\frac{L}{B}(t_{min} - q_0) + p_0\right)}{s^2 + \left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R0}\right)s + \left(\frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d}\right) + \left(\frac{LC_d^2}{2NB}\right)e^{-R_0 s}} \tag{23}$$

$$\delta Q(s) = \frac{y_6}{s^2 + x_1 s + x_3 + \frac{x_2}{2}e^{-R_0 s}} \tag{24}$$

Where,

$$y_6 = \frac{1}{s}\ \frac{C_d^2}{2N}\ \left(\frac{L}{B}(t_{min} - q_0) + p_0\right)$$

Theorem 2

Given the wireless network parameters C_d, C_u, N, R_0 and B, wireless network system given in (2) to (4), has the approximate solution of q(t) give by,

$$q(t) = q_0 + y_6\left[\frac{e^{xt}}{(x - y)x} - \frac{e^{yt}}{(x - y)y} + \frac{1}{xy}\right]$$

Provided P_{max} and β satisfies the conditions as

$$0 < p_{max} \le \frac{-\xi_2 + \sqrt{\xi_2^2 - 4\xi_1\xi_3}}{2\xi_1}$$

$$0 < \beta \le \frac{-A_2 + \sqrt{A_2^2 - 4A_1 A_3}}{2A_1}$$

Where ξ_i's and A_i 's are given in (29).

Proof:

Expanding $e^{-R_0 s}$, using Taylor's theorem about the stability point discarding the terms of order three and higher,

$$e^{-R_0 s} = 1 - R_0 s + \frac{R_0^2 s^2}{2}$$

From (16), $s^2 + x_1 s + x_3 + \frac{x_2}{2}e^{-R_0 s}$. This simplifies to

$$s^2 + \left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0}\right)s + \left(\frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d} + \frac{LC_d^2}{2NB}\left(1 - R_0 + \frac{R_0^2 s^2}{2}\right)\right)$$

$$\left(1 + \frac{LR_0^2 C_d^2}{4NB}\right)s^2 + \left(\frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0} - \frac{LR_0 C_d^2}{2NB}\right)s + \left(\frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d} + \frac{LC_d^2}{2NB}\right)$$

Put $\eta 1 = \left(1 + \frac{LR_0^2 C_d^2}{4NB}\right)$, $\eta 2 = \frac{\beta}{R_0} + \frac{2N}{R_0^2 C_d} + \frac{1}{R_0} - \frac{LR_0 C_d^2}{2NB}$, $\eta 3 = \frac{\beta}{R_0^2} + \frac{2N}{R_0^3 C_d} + \frac{LC_d^2}{2NB}$

$$\eta_1 s^2 + \eta_2 s + \eta_3 \tag{25}$$

If $\Delta > 0$,equation (25) has distinct roots given by,

$$x, y = \frac{-\eta_2 \pm \sqrt{\eta_2^2 - 4\eta_1\eta_3}}{2\eta_1} \tag{26}$$

where, x takes + and y takes – of ±.

The discriminate of (26) is positive. After simplification for the discriminant, and expressing in terms of L and β, we get,

$$\xi_1 L^2 + \xi_2 L + \xi_3 > 0 \tag{27}$$

$$A_1\beta^2 + A_2\beta + A_3 > 0 \tag{28}$$

where,

$$\xi_1 = \left(\frac{C_d^2 R_0}{2NB}\right)^2$$

$$\xi_2 = \frac{4\beta C_d}{NB} + \frac{4C_d}{R_0 B} + \frac{C_d}{NB}$$

$$\xi_3 = \frac{4\beta}{R_0^2} - \left(\frac{\beta}{R_0} + \frac{1}{R_0} - \frac{2N}{R_0^2 C_d}\right)^2 \tag{29}$$

$$A_1 = \frac{1}{R_0^2}$$

$$A_2 = \frac{4N}{R_0^3 C_d} - \frac{2}{R_0^2} - \frac{2LC_d^2}{NB}$$

$$A_3 = \frac{1}{R_0} + \frac{4N^2}{R_0^4 C_d^2} - \frac{4N}{R_0^3 C_d} - \left(\frac{LC_d^2 R_0}{2NB}\right)^2 - \frac{LC_d^2}{NB} - \frac{4LC_d}{R_0 B}$$

Solving (27) for $L=P_{max}$ and (28) for β, we get

$$0 < p_{max} \le \frac{-\xi_2 + \sqrt{\xi_2^2 - 4\xi_1\xi_3}}{2\xi_1} \tag{30}$$

$$0 < \beta \le \frac{-A_2 + \sqrt{A_2^2 - 4A_1A_3}}{2A_1} \tag{31}$$

From Equation (24) and (26),

$$\delta Q(s) = \frac{y_6}{s(\eta_1 s^2 + \eta_2 s + \eta_3)}$$

$$\delta Q(s) = \frac{y_6}{s(s-x)(s-y)}$$

Using partial fraction,

$$\delta Q(s) = y_6\left[\frac{1}{x(x-y)}\frac{1}{(s-x)} - \frac{1}{y(x-y)}\frac{1}{s-y} + \frac{1}{xy}\frac{1}{s}\right]$$

Taking Laplace transform,

$$\delta q(t) = y_6\left[\frac{e^{xt}}{x(x-y)} - \frac{e^{yt}}{y(x-y)} + \frac{1}{xy}\right]$$

$$q(t) = q_0 + y_6\left[\frac{e^{xt}}{x(x-y)} - \frac{e^{yt}}{y(x-y)} + \frac{1}{xy}\right] \tag{32}$$

Theorem 3

Given the wireless network parameters C_d, C_u, N, R_0 and B, the instantaneous queue length converges to the target, $T = \frac{(t_{min}+w_{max})}{2}$ if and only if RED control parameter, P_{max} and NTG parameter β satisfies the conditions as

$P_{max} = K_1 K_2 + K_3$

$\beta = K_4 K_5$ where K_i 's are given by (36).

Proof:

From equation (24),

$$\lim_{t\to\infty} \delta q(t) = \lim_{s\to 0} sQ(s) = \lim_{s\to 0} \frac{y6}{s^2 + x_1 s + x_3 + \frac{x_2}{2} e^{-R_0 s}}$$

$$\lim_{t\to\infty} \delta q(t) = \lim_{s\to 0} sQ(s) = \frac{y_6}{x_3 + x_2/2} + q_0$$

$$\lim_{t\to\infty} q(t) = q_0 + \lim_{t\to\infty} \delta q(t)$$

$$\lim_{t\to\infty} q(t) = q_0 + \frac{y6}{x3 + \frac{x2}{2}} \tag{33}$$

$$Let \ \lim_{t\to\infty} q(t) = \frac{t_{min} + w_{max}}{2}$$

$$P_{max} = K_1 K_2 + K_3 \tag{34}$$

$$\beta = K_4 K_5 \tag{35}$$

Where

$$K_1 = \frac{4N^2}{R_0^3 C_d^3} + \frac{2\beta N}{R_0^2 C_d^2}$$

$$K_2 = 2q_0 - t_{min} - w_{max} \tag{36}$$

$$K_3 = \frac{4\beta N}{R_0 C_d} + \frac{4N^2}{R_0^2 C_d^2}$$

$$K_4 = \frac{P_{max} R_0^2 C_d^2 - 4N^2}{2N + 4NR_0 C_d}$$

$$K_5 = 1 + \frac{1}{R_0 C_d}(2q_0 - t_{min} - w_{max})$$

Theorem 4

The wireless network system given by equations (2)-(4) is asymptotically stable in terms of the state variable δw(t) and δq(t), if the queue level q_0 at equilibrium point satisfies

$$\frac{t_{min}+w_{max}}{2}-\frac{R_0C_d}{2}<q_0\le\frac{t_{min}+w_{max}}{2}-\frac{R_0C_d}{2}-\frac{\xi_2}{\xi_7}+\frac{\xi_8}{\xi_7}\sqrt{\xi_6}$$

Proof:

Using (34) in (30)

$$0<K_1K_2+K_3\le\frac{-\xi_2+\sqrt{\xi_2^{2}-4\xi_1\xi_3}}{2\xi_1}$$

Subtitling for K1, K2 and K3 from (36), and simplifying for q_0, we get

$$\frac{t_{min}+w_{max}}{2}-\frac{R_0C_d}{2}<q_0\le\frac{t_{min}+w_{max}}{2}-\frac{R_0C_d}{2}-\frac{\xi_2}{\xi_7}+\frac{\xi_8}{\xi_7}\sqrt{\xi_6} \quad (37)$$

$$\xi_6=\frac{C_d^{4}}{N^2B^2}\left[\left(2\beta+1+\frac{4N}{R_0C_d}\right)^2+(\beta-1)^2+\frac{4N}{R_0C_d}\left(\frac{N}{R_0C_d}-\beta-1\right)\right]$$

$$\xi_7=\frac{2C_d^{3}}{NB^2}\left(\beta+\frac{2N}{R_0C_d}\right) \quad (38)$$

$$\xi_8=\frac{C_d^{2}}{NB}$$

Simulation and Performance Analysis

A number of simulation experiments are conducted to evaluate the performance of TCP with NDG loss-predictor. All simulations are performed using Matlab R2009b. The network model is as illustrated in Figure 1. Computer-1,2,and 3 are the sources, R_1 and R_2 are the routers, and D_1 , D_2, and D_3 are the mobile stations which are the destinations. We have TCP Reno connections from sources to destinations. These connections share the link R_1 and R_2. The TCP which has been modeled represent the last hop transmission between R_2 and the destinations D_1, D_2 and D_3. In a network, Cliff is the point at which throughput approaches zero. Throughput falls off rapidly after this point. Knee is the point at which throughput starts increasing.

5.1 Experiment 1: Un-stable network system.

In this experiment, the link between R_1 and R_2 is the bottleneck link. Packet size is 1000 bytes, P_{max}=0.05, queue buffer at the router has a minimum threshold value, t_{min}=200 packets, maximum threshold value, W_{max}= 500 packets, initial RTT= 50 ms, C_d=10 Mbps, Cu = 500Kbps, N =10, beta=0.1, propagation delay, t_p=50ms, initial rtt-delay, R_0=100ms.

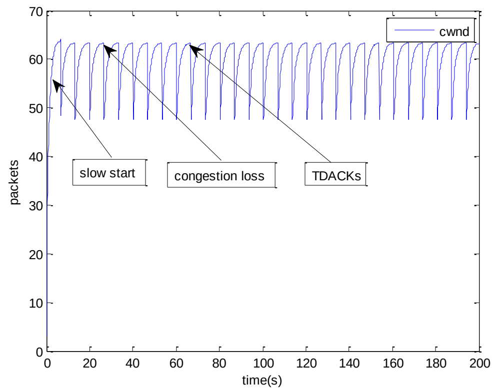

Figure 3. Sender window dynamics.

In the beginning Sender window begins with slow-start (SS) phase. Increases its window size by one packet for every receive of an acknowledgement. When it notices congestion loss or receives TDACKs, reduces the window size to half of the current size, and initiates again S.S phase. When the packet loss is due to transmission, TCP window assume that the loss is due to congestion and reduce the cwnd. When the NDG loss-predictor predicts that next packet loss is due to wireless transmission, cwnd initiates immediate-recovery and regain the loss. Figure 3 illustrates the traces of sender window size. cwnd varies over 47 to 64 packets.

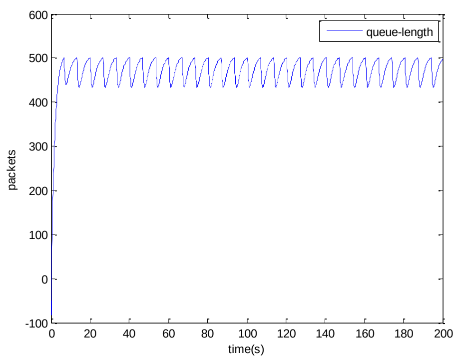

Figure 4. Queue length at the bottleneck link.

Queue length is measured at the ingress point of the bottleneck link. Queue length depends on the sender window size. Queue length increases as the cwnd increases. In the experiment minimum and maximum threshold values are 200 and 500 packets respectively. But the queue length varies over the range 433 to 500 packets because of the operation of immediate-recovery. Figure 4 describes the performance of instantaneous queue length.

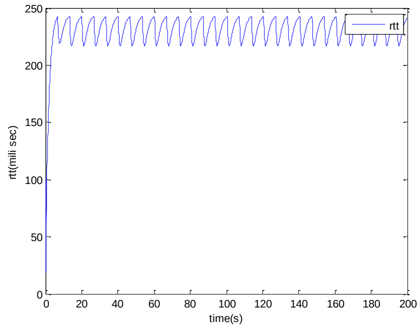

Figure 5. variation of rtt-delay.

Round trip time depends on queue length of the router. In this experiment, RTT is modelled with variable queuing delay and a constant propagation delay of 50 milliseconds. Figure 5 give the variation in RTT value which varies over the range of [102,242] milliseconds..

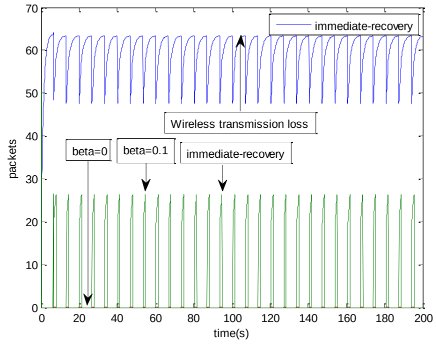

Figure 6. Immediate-recovery when $f_{NDG} \leq 0$.

The problem with TCP when traverses wireless link is explicate assumption that the packet loss is due to congestion. To overcome this problem, the model is integrated with NDG loss-loss predictor function. When f_{NDG} value is >0, sender TCP determines that loss is due to congestion and congestion control algorithm is invoked by tuning β=0. . When f_{NDG} value is ≤ 0, sender TCP determines that loss is due to wireless transmission and to recover from the loss, immediate-recovery algorithm is invoked by tuning β=0.1. The traces of graph of Figure 6 illustrate the performance of the immediate-recovery algorithm. Immediate recovery varies between [19, 26] packets.

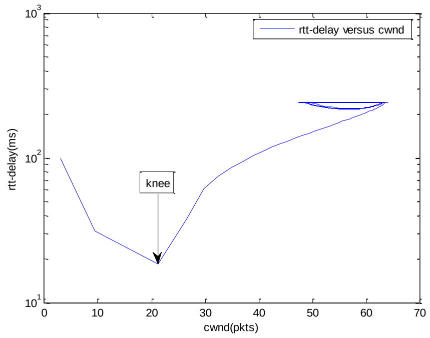

Figure 7. RTT-delay versus cwnd.

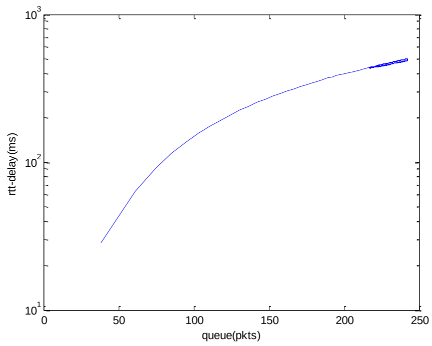

Figure 8. Queue-delay versus rtt-delay.

In the beginning of the simulation, there was no queue length at the router resulting increase in cwnd, decrease in rtt-delay. As the sender window size increase, more and more packets are pumped into the network increasing the queue length in the bottleneck link. This leads to faster increase in the rtt-delay. Figure 7 gives the variation of rtt-delay with cwnd. Figure 8 illustrates the increase of rtt-delay with queue-delay.

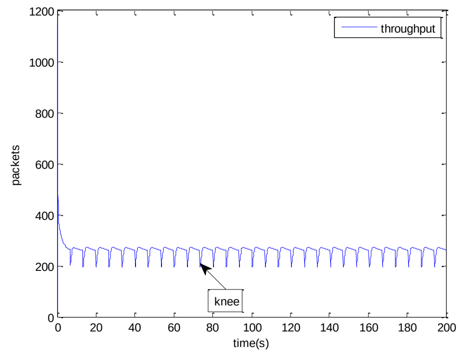

Figure 9. Throughput versus time.

Throughput varies with sender window. It varies over the range of [210, 255] packets. Figure 9 illustrates the graph of variation of throughput with respect to time in seconds.

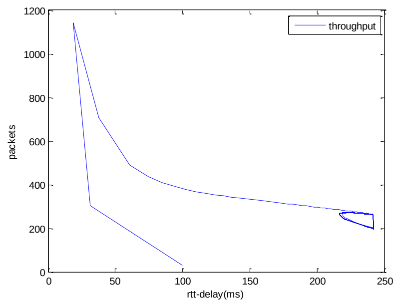

Figure 10. Throughput versus rtt-delay.

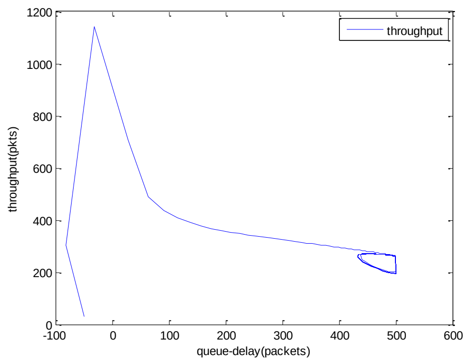

Figure 11. Throughput versus queue-delay.

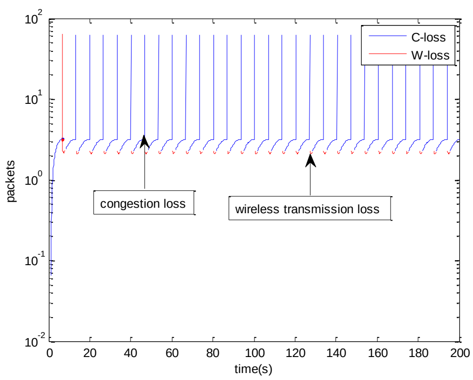

Figure 12. pkt. losses due to congestion and transmission.

The graph of Figure 10 illustrates the variation of throughput with respect to rtt-delay. In the beginning of the simulation, queue length at the router is less, packet loss due to congestion is zero, throughput increases faster. When congestion established because of increased of load, packet loss increased and decrease in throughput. Figure 11 illustrates the variation of throughput with respect to queue-delay. The traces of the graph in Figure 12 illustrate packet losses due to congestion and packet losses due to wireless transmission at the ingress point of the router.

Analysis performance metrics of f_{NDG}

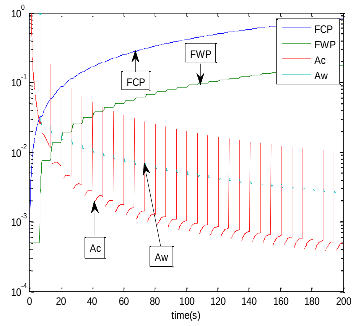

Figure 13. FCP, FWP, Ac and Aw.

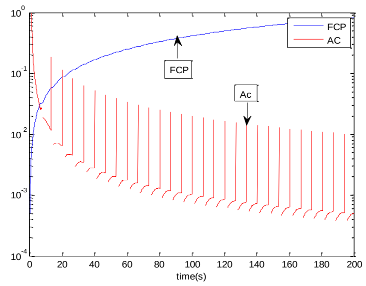

Figure 14. FCP and Ac.

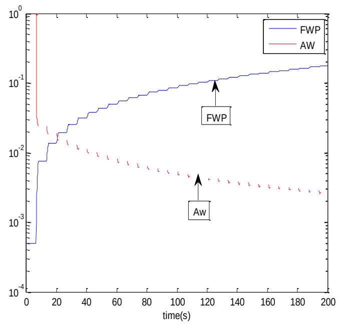

Figure 15. FWP and Aw.

This experiment was conducted to analyse the performance ability of NDG loss-predictor to distinguish congestion loss from wireless transmission loss. Important performance analysis metrics are, (i) Frequency of congestion loss prediction (FCP): FCP is obtained by dividing the number of times the loss-predictor predicts that the next loss will be due to congestion, by the total number of times the predictor was evaluated during the TCP connection. Two counters were introduced to count the number of times the congestion and the transmission losses accrues. The estimated values were used in the calculation of FCP, FWP, Ac and Aw. In this experiment, number of times the NTG loss-predictor predicts that the next loss will be due to congestion=1649. Total number of times the predictor is evaluated during a TCP connection=2000. FCP=1649/2000=0.8245(approximately 82%). (ii) Frequency of wireless loss prediction (FWP): FWP is obtained by dividing the number of times the NDG loss-predictor predicts that the next loss will be due to wireless transmission error, by the total number of times the predictor was evaluated during the TCP connection. Number of times the loss-predictor is predicted that the next loss will be due to wireless=351. Total number of times the predictor is evaluated during a TCP connection=2000. FWP= 351 /2000=0.1755 (approximately 18%). (iii) Congestion loss prediction (Ac): Ac is the fraction of packet losses due to congestion, diagnosed by NTG loss-predictor. (iv) Wireless loss prediction (Aw): Aw is the fraction of packet losses due to wireless transmission errors diagnosed by NTG loss-predictor. In the process of simulation it is observed that approximately 82% of the losses are due to congestion and 18% of the losses are due to wireless transmission as predicted by the loss-predictor. The graph of Figure 13 shows the variation of FCP, FWP, Ac and Aw with respect to time. The graph of Fig.14 shows the variation of FCP and Ac with respect to time. The graph of Figure 15 shows the variation of FWP and Aw with respect to time.

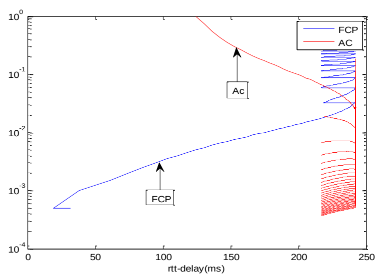

Figure 16. FCP and Ac w.r.t rtt-delay.

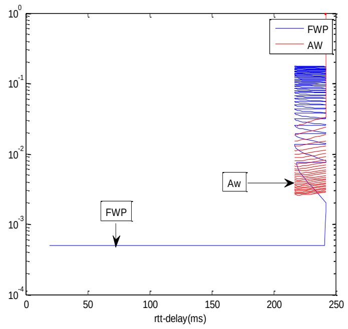

Figure 17. FWP and Aw w.r.t rtt-delay.

The round trip time (RTT) is the total time taken by a packet to travel from source to destination and the ACK from destination to source. In our work, RTT includes variable queuing delay and a constant propagation delay. In the experiment, we assume that both wired and wireless medium has a constant propagation delay of 50 ms. Thus, RTT varies over the range [102, 242] milliseconds. Since RTT depends on queue length, we observe that increase in queue length leads to increase in RTT value and vice versa. Larger the queue length implies higher the congestion. Figure 16 describe the performance of FCP and Ac. FCP increase slowly in the beginning and becomes high over the RTT range 200 to 250 . Increase in congestion is responsible for increase in FCP. The graph is also associated with the fraction of packet losses due to congestion diagnosed by NDG loss-predictor. Figure 17 illustrates the traces of FWP and Aw with respect to rtt-delay. FWP is almost constant till rtt-delay reach 220 ms, suddenly increases when delay is 220-245 ms. This may be because of burst in traffic and wireless transmission impairments. The graph is also associated with Aw, the fraction of packet losses due to wireless transmission errors diagnosed by NDG loss-predictor.

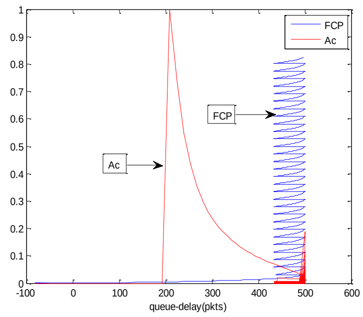

Figure 18. FCP and Ac w.r.t queue-delay.

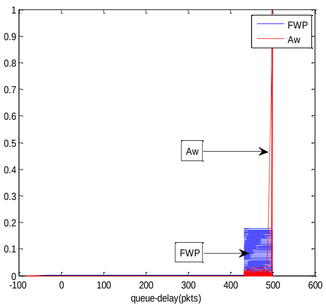

Figure 19. FWP and Aw w.r.t queue-delay.

Queue length is measured at the bottleneck link of R_2. We consider a variable queue which depends on the components such as (i) traffic due to arrival of the packets from TCP- sources,(ii) decrease in queue length due to servicing of the packets by the router and delay of the packet departure. NTG loss-predictor built based on congestion avoidance strategy, so f_{NTG} is increasing with increase in queue length. As a result, FCP increases slowly in the beginning and high with the increase queue-delay. The traces of Figure18 illustrate the variation of FCP and Ac w.r.t queuing-delay. The traces of Figure 19 illustrate the variation of FWP and Aw w.r.t queuing-delay. Sum of the fraction of packet losses due to congestion (Ac) is 11.06 packets and sum of the fraction of packet losses due to transmission (Aw) is 4.4 packets for a total of 120030 packets transported during simulation. The traces of Figure 18 show the variation of FCP and Ac with respect to queue-delay. The traces of Figure 19 show the variation of FWP and Aw with respect to queue-delay.

Experiment 2. Stable Network System

The objective of stability analysis is to minimise the occurrence of queue overflow and underflow, thus reducing the packet loss. Majority of the end-point control techniques regulate the traffic demands according to the resources available in the wireless network. In an end-to-end control scheme, stability analysis can achieve optimality. A time-delay control theory is applied for the analysis of FCP, Ac, FWP, and Aw. Knowing the wireless network parameters such as C_d, Cu, N, R_0 (Avg.rtt-delay), and B (RED parameter, determined by maximum minus minimum queue buffer threshold values). we derive a stability range for P_{max}(maximum packet dropping probability) and β (f_{NDG} parameter for immediate-recovery). The relations are illustrated in equation (19) and (20) with reference to theorem-1. Given, Cd=10Mbps, Cu=500Kbps, B=300packets, N=10, R_0=100 ms, t_p=50ms, at the equilibrium point we get P_{max}=0.0077, and β=0.1638.

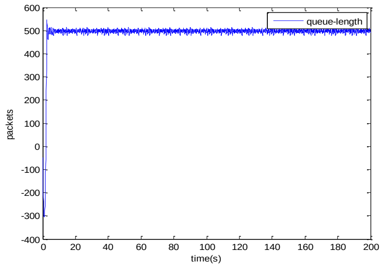

Figure 20. Stable bottleneck queue.

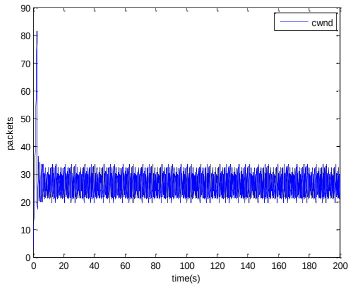

Figure 21. Stable sender window.

The graphs in Figure 20 and Figure 21 describe the stable queue length and sender window size respectively with respect to time. Queue length in the bottleneck link fluctuates over the range of [495, 500] packets. The sender window fluctuates over the range of [19, 33] packets. Since queue length stabilises over a definite range based on the available resources, the packet losses due to congestion is very small. The packet losses due to wireless transmission remain unchanged.

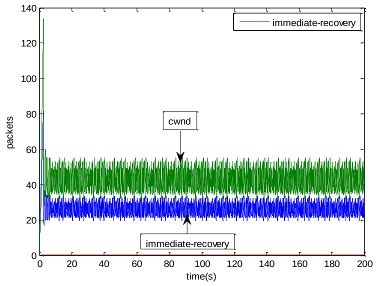

Figure 22. Immediate-recovery of source w.r.t f_{NDG}.

Figure 22 presents the immediate-recovery of the sender window size when the loss predictor predicts that next packet loss is due to transmission. Recovery is over the range[35, 40].

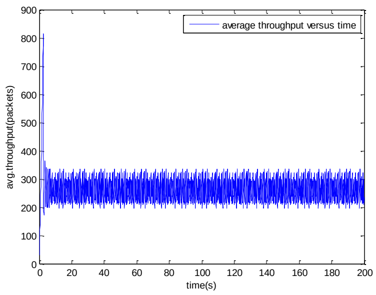

Figure 23. avg. Throughput w.r.t time.

The traces of Figure 23 illustrate variation of throughput with respect to time.

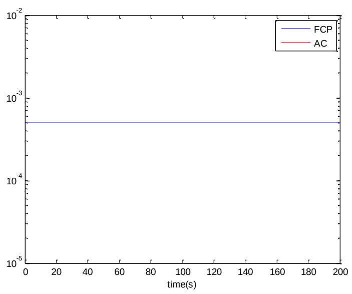

Figure 24. stable FCP and Ac w.r.t time

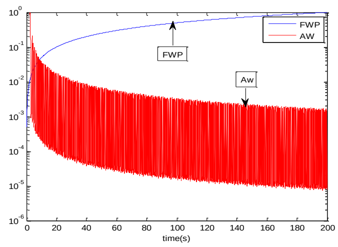

Figure 25. FWP and Aw w.r.t. time

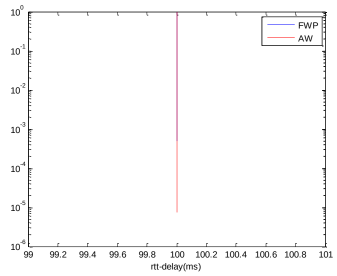

Figure 26. FWP and Aw w.r.t. rtt-delay.

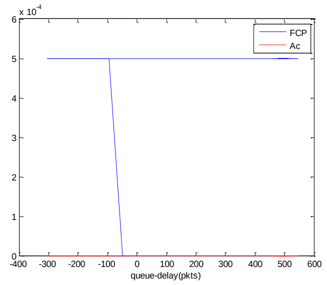

Figure 27. FCP and Ac w.r.t. queue-delay.

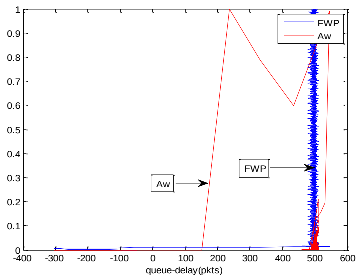

Figure 28. FCP and Ac w.r.t. queue-delay.

Number of times the loss predictor predicted that the next loss is due to congestion= 1.Total number of times the predictor evaluated during a TCP connection=2000. FCP=1/2000=0.0005 (approximately 0%). Number of times the loss predictor predicted that the next loss is due to wireless=1999. Total number of times the predictor evaluated during a TCP connection=2000. FWP=1999/2000= 99.99 (approximately 100%). Figure 24 and Figure 25 illustrate the NDG prediction of congestion loss and transmission losses respectively. Sum of the fraction of packet losses due to congestion (Ac) is 0 packets and sum of the fraction of packet losses due to transmission (Aw) is 9 packets for a total of 52293 packets transported. Fig.26 illustrates the traces of the graph of variation of FWP and Aw with respect to rtt-delay. Figure 27 and Figure 28 illustrate the traces of FWP and Aw with respect to queue-delay.

Experiment 3. Queue Convergence Analysis

In a bust traffic, sender window and queue length exhibit oscillatory behaviour. The objective of analysis of convergence of the queue length is to minimise oscillatory nature of RED router. Using q_0 as the initial value, queue length converges faster to the given target value. This helps in improving the fairness of the system. Knowing the wireless network parameters C_d , C_u, N, R_0, and B, we derive a range of convergence for $P_{max,}$ β, and q_0 using the relations (34),(35) and (37). Using (37) estimate q_0, by using this value of q_0 and (34) find p_{max}, by using p_{max} and (35) find β. Given C_d=4Mbps, C_u=500Kbps, t_{min}= 200 packets, w_{max}= 500 packets, N=10, R_0=100 ms, B=300 packets, target value, T=350 packets, we get, q_0=313, P_{max}=0.0054, and β=0.0018. The range of convergence of queue length is (305.12, 320.8). The traces of the graph of Figure 29 illustrate the convergence of queue length for a given target value.

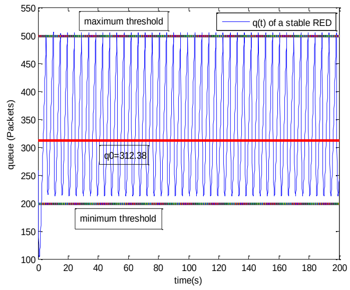

Figure 29. Queue convergence T=350.

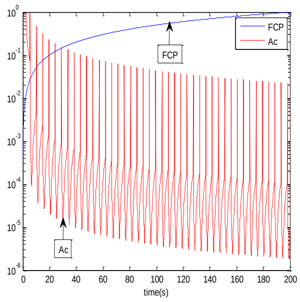

Figure 30. FCP and Ac, when T=350.

Duration of the simulation time, the value of loss-predictor function f_{NDG} is 0<0.5, predicting FWP is negligible and Aw is near to zero. Majority of the predictions are due to congestion losses. The traces of Figure 30 describe the frequency of congestion losses predicted by the loss predictor, and Figure 31 describes the fraction of packet losses due to congestion. Total number of packet losses due to congestion is 11 packets.

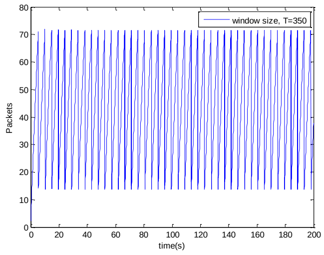

Figure 31. Cwnd when T=350.

Sender window varies over the range of [13,71] packets where majority of the values lies in the range [35,55] packets. Figure 31 gives the traces of sender window size.

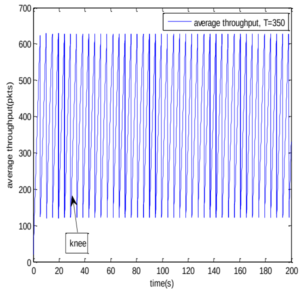

Figure 32. Throughput, when T=350.

Figure 32 describes the performance of throughput with respect to time. It varies over a range of [212, 627] packets where majority of the values over the range of [300, 500] packets.

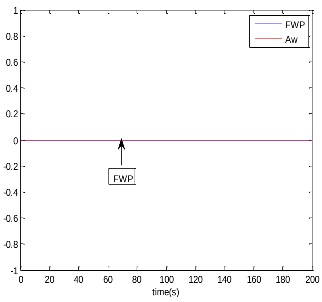

Figure 33. FWP and Aw, when T=350.

Figure 33 illustrate that frequency of wireless loss, FWP=0, Aw=0.

Conclusion

The work presented in this paper is an original research to improve the performance of TCP in wireless networks. The proposed transport model gives and end-to-end solution. The main problem of TCP has an implicit assumption that all packet loss is due to congestion which is resolved by introducing NDG loss-predictor. The NDG loss-predictor is a congestion avoidance method. NDG loss-predictor parameter β is integrated with the system model, and can tune depending on the prediction of the losses. Statistical analysis of FCP,FWP, Ac and Aw are made. After a successful implementation of loss detection in TCP, we tried to minimise the packet loss due to congestion by introducing the concept of stability. The stability boundary of two important tuning parameter P_{max} and β is derived in terms wireless network parameters. Knowing the wireless network resources and tuning these parameters, the system becomes asymptotically stable. After successful control on congestion loss, we discuss convergence analysis of queue length at the ingress point of the router. Condition for queue length convergence at the router is established. This helps in resolving the oscillatory problem of RED router. Thus, the model presented in this work is efficient, fair and adaptable to the wireless environment.

References

[1] Kai Xu, Ye Tian, and Nirwan Ansari," TCP-Jersey for Wireless IP Communications", IEEE journal on selected areas in communications, Vol. 22, No. 4, May 2004.

[2] Sally Floyd and Van Jacobson," Random Early Detection Gateways for Congestion Avoidance", IEEE/ACM Transactions on Networking, August 1993.

[3] Francois Baccelli & Ki Baek Kim,' TCP Throughput Analysis under Transmission Error and Congestion Losses", IEEE INFOCOM, 0-7803-8356-7, 2004.

[4] A. Bakre and B. R. Badrinath, "I-TCP: Indirect TCP for Mobile Hosts," In Proceedings of 15th International Conf. on Distributed Computing Systems (ICDCS), May 1995.

[5] K. Brown and S. Singh, "M-TCP: TCP for Mobile Cellular Networks," *In Proceedings of INFOCOM '96*, 1996.

[6] H. Balakrishnan, S. Seshan, E. Amir and R. H. katz., "Improving TCP/IP Performance Over Wireless Networks," In Proceedings of ACM MOBICOM '95, 1995.

[7] H. Balakrishnan and R. H. Katz, "Explicit Loss Notification and Wireless Web Performance," *In Proceedings of IEEE GLOBECOM '98*, 1998.

[8] P. Sinha et al., "WTCP: A Reliable Transport Protocol for Wireless Wide-Area Networks," *In Proceedings of ACM MOBICOM 1999*, Aug. 1999.

[9] S. Mascolo and C. Casetti, "TCP Westwood: Bandwidth Estimation for Enhanced Transport over Wireless Links," *In Proceedings of MOBICOM '2001*, 2001.

[10] Seongho Cho, and Heekyoung Woo, '' TCP Performance Improvement with ACK Pacing in Wireless Data Networks", School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Republic of Korea.2005.

[11] Eric Hsiao-Kuang Wu, and Mei-Zhen Chen," JTCP: Jitter-based TCP for heterogeneous wireless networks", IEEE journal on selected areas in communications, Vol. 22, No. 4, May 2004.

[12] Masashi Nakata, Go Hasegawa, Hirotaka Nakano, "Modeling TCP throughput over wired/wireless heterogeneous networks for receiver-based splitting mechanism", Graduate school of Information Science and Technology, Osaka University, Japan.

[13] Wei Zhang, Liansheng Tan, and Gang Peng, " Dynamic queue level control for TCP/RED systems in AQM routers", Computers and Electrical Engineering, 35, 59-70, 2009.

[14] Liansheng Tan, Wei Zhang, Gang Peng and Guanrong Chen, "Stability of TCP/RED system in AQM routers", IEEE Transactions on automatic control, vol. 51, no. 8, 2006.

[15] L.Tan, W.Zhang, G.Peng and G.Chen, "Stability of TCP/RED systems in AQM routers", IEEE Trans. Automatic control, Vol. 51, No. 8, pp 1393-1398, August 2006.

[16] W.Zhang. L.Tan, and G.Peng, "Dynamic queue level control of TCP/RED systems in AQM routers", Computers and Electrical Engineering, Vol.35, No. 1, PP 59-70, 2009.

[17] Hiroaki Mukaidani, Lin Cai, Xuemin Shen, "Stable queue management for supporting TCP flows over wireless networks", IEEE ICC, 978-1-61284-231-8/11, 2011.

[18]Saad Biaz, and Nitin H.Vaidya, "Sender-based heuristics for distinguishing congestion losses from wireless transmission losses", technical report-98-013, Department of Computer Science, Texas Aand M University, USA, 2003.

[19] Z.Wang, and J.Crowcroft,"A new congestion control scheme: Slow start and search (tri-s)', ACM Computer communication Review, vol. 21, pp.32-43, jan. 1991.

[20] Anurag Kumar, D.majunath, Joy Kuri, "Communication Networking, an analytical approach", Morgan Kaufmann publisher an imprint of ELSEVIER, 2005.

[21] Raj Jain, "A delay-based approach for congestion avoidance in interconnected heterogeneous computer networks",ACM Computer communication review, vol. 19, pp 56-71, 1989.

[22] David A. Hayes and Grenville,"Revisiting TCP congestion control using delay gradient", Centre for advanced internet architectures, Swinburne University of Technology, Melbourne, Australia, 2011.

[23]] Raj Jain, "Congestion control in computer networks: Issues and trends", IEEE, Networking, pp.24-30, 1990.

Authors

Goudru N.G, received his Ph.D degree in Mathematics from Gulbarga University, Karnataka in 1989, M.Sc (Applied Mathematics) degree from Karnataka University, Dharwar in 1981, M.S (Software Systems) degree from BITS, Pilani in 1994. He is working as a professor in the department of Mathematics, BMS Institute of Technology (affiliated to visvesvaraya Technological University), Bangalore, Karnataka. His major areas of research are in Computational fluid dynamics and wireless mobile networks.

Vijaya Kumar B.P, received his Ph. D degree in Electrical and Communication Engineering. department from Indian Institute of Science (IISc), Bangalore in 2003, M.Tech degree in Computer Science and Technology from the University of Roorkee (Presently Indian Institute of Technology, IITR), with honors in 1992 and Bacholers degree in Electronics and Communications from Mysore University with Distinction in the year 1987. He is currently working as a professor and Head of Information Science and Engineering department, MS Ramaiah Institute of Technology(affiliated to visvesvaraya Technological University), Bangalore, Karnataka, India, where he is involved in research and teaching UG and PG students, and his major area of research are Computational Intelligence applications in Mobile, Adhoc and Sensor networks.