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Queue Dynamics Analysis of TCP Veno with RED

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***Abstract*— In this paper, we aim to study the queue dynamics of TCP Veno with RED in the wired-wireless heterogeneous networks. We first develop a fluid-flow model of TCP Veno with RED over heterogeneous network, and then use the classical linear feedback control theory to analyze it. Analysis results reveal the relationship between the RED queue oscillation and the network parameters. We use simulation tool to validate our analysis, and show how to stabilize the router queue and improve the co-existence of TCP Veno with TFRC.**

I. Introduction

TCP is a connection-oriented, reliable and in-order transport protocol. The current legacy TCP version is Reno TCP [1]. However, with rapid progress of wireless technologies, Reno TCP is increasingly being challenged. For example, Reno mistakes the random loss (that is induced by wireless transmission error) as congestion signal, and unnecessarily reduces the sending rate, resulting in significant performance degradation. To solve this problem, TCP Veno [2], a sender-side TCP enhancement, was recently proposed. TCP Veno makes use of the congestion monitoring scheme in TCP Vegas [3] and intelligently integrates it into Reno TCP. Real network and live Internet measurements have validated Veno's significant performance improvement in the wireless networks and its harmonious co-existence with TCP Reno in the wired networks.

In this paper, we aim to study the queue dynamics of TCP Veno with RED [4] in the wired-wireless heterogeneous networks. We first develop a fluid-flow model of TCP Veno with RED over heterogeneous network, and then use the classical linear feedback control theory to analyze it. Analysis results reveal the relationship between the RED queue oscillation and the network parameters. We use network simulation tool to validate our analysis.

The queue oscillation can have negative effect on co-existing protocols, such as TCP-Friendly Rate Control (TFRC) [5]. TFRC is a rate-based congestion control mechanism. It continuously measures the round trip time and packet loss rate, and then uses TCP response function to calculate its sending rate. The main aims of TFRC are fairness and smoothness. Fairness means TFRC and TCP flows should fairly share the network capacity when co-existing with each other. Smoothness means TFRC throughput should not fluctuate drastically. Smoothness is measured in this paper by Coefficient of Variation (CoV) of TFRC throughput sampled every 0.1 second. Due to the RED queue oscillation, the round trip time measured by TFRC would vary in a large range, and hence cause TFRC throughput change drastically. In this paper, our analysis results provide some guidelines of tuning RED parameters to stabilize router queue, and hence improve TFRC smoothness when co-existing with TCP Veno. Meanwhile, we observe that, TCP Veno and TFRC fairly share the bandwidth in different network environments.

The rest of this paper is organized as follows. Section II is the brief review of TCP Veno. In Section III, we develop the fluid-flow model of TCP Veno with RED over wired-wireless heterogeneous networks. In Section IV, we use the classical linear feedback control theory to analyze its stability margins. In Section V, we use network simulation tool to validate our analysis and show how to improve the co-existence of TCP Veno with TFRC. Section VI is the conclusion.

II. TCP Veno

TCP Veno borrows the idea of congestion monitoring scheme in Vegas to estimate the network in congestive state or non-congestive state. Specifically, Veno uses the following formula to estimate the number of packets accumulated at the router.

$$N = (\frac{cwnd}{BaseRTT} - \frac{cwnd}{RTT}) \times BaseRTT \quad (1)$$

where $BaseRTT$ is the minimum of all measured RTT (round trip time), and RTT is the actual round trip time of a tagged packet. If $N \geq \beta$, the network is said to have evolved into congestive state. Otherwise, it is in the non-congestive state. β is set to 3. Based on different network states, Veno modifies the Reno AIMD algorithm as follows.

Multiplicative Decrease:
If $(N < \beta)$ $\quad ssthresh = cwnd \cdot 4/5$;
  else $\quad ssthresh = cwnd/2$;
Additive Increase:
If $(N < \beta)$ $\quad cwnd{+}= 1/cwnd$ for every new ACK
  else $\quad cwnd{+}= 1/cwnd$ for every other new ACK

Other components, i.e. slow start, Fast retransmit and Fast recovery, remain unchanged.

III. Fluid-flow model of TCP Veno with RED

The fluid-flow model is composed of three parts: heterogeneous network, RED queue management and Veno window evolution. We first extend the wired network model in [6] to comprise wireless links. As in [6], the network comprises of L links with capacity $c_l, l \in L$. There are n sources indexed by i. Each source i uses a set of links $Li \subseteq L$. So we have a $L \times n$ routing matrix $\{M_{li}\}$, where $M_{li} = 1$ if $l \in L_i$, or 0 otherwise. The round trip time of source i at time t is $R_i(t)$:

$$R_i(t) = T_i + \sum_l M_{li} \frac{q_l(t)}{c_l}$$

where T_i is the round trip propagation delay of source i and $q_l(t)$ is the instantaneous queue in link l at time t. Denote the loss probability of link l at time t is $p_l(t)$. Assuming that $p_l(t)$ is small, then the end-to-end loss probability at time t, $v_i(t)$, is approximately expressed as,

$$v_i(t) = \sum_l M_{li} p_l(t - R^b_{li}(t))$$

where $R^b_{li}(t)$ is the backward delay from link l to source i. Denote the congestion window size of source i at time t is $w_i(t)$, so the sending rate of source i at time t is $x_i(t) = \frac{w_i(t)}{R_i(t)}$. Assuming the last-hop link is wireless link with random loss rate γ_i. So the aggregate arriving rate of link l at time t is:

$$y_l(t) = \sum_i M_{li} \frac{w_i(t - R^f_{li}(t))(1 - \gamma_i)}{R_i(t - R^f_{li}(t))}$$

where $R^f_{li}(t)$ is the forward delay from source i to link l. For all links $l \in L$, given the aggregate arriving rate and link capacity, we can calculate the instantaneous queue length $q_l(t)$ derivative ($q_l(t) > 0$) by:

$$\dot{q}_l(t) = y_l(t) - c_l = \sum_i M_{li} \frac{w_i(t - R^f_{li})(1 - \gamma_i)}{R_i(t - R^f_{li})} - c_l \qquad (2)$$

The RED model is the same as [6][7]. RED calculates the average queue length $r_l(t)$ by: $r_l(k+1) = (1 - \lambda_l) r_l(k) + \lambda_l q_l(k)$. λ_l is the queue averaging weight of link l: $0 < \lambda_l < 1$. We only consider the system operates in the region $min_{th} \leq r_l(t) \leq max_{th}$, where min_{th}, max_{th}, and p_{max} are RED minimum threshold, maximum threshold, and maximum loss probability, respectively. So, the drop probability is $p_l(t) = \rho_l(r_l(t) - min_{th})$, where $\rho_l = p_{max}/(max_{th} - min_{th})$. Denote $\alpha = c_l log(1 - \lambda_l)$, according to [6] we know that,

$$\dot{p}_l(t) = -\alpha_l(p_l(t) + \rho_l min_{th}) + \alpha_l \rho_l q_l(t) \qquad (3)$$

Now we model TCP Veno behavior in the congestion avoidance phase. At time t, TCP Veno source i sending rate is $x_i(t)$, and ACK receiving rate is $x_i(t - R_i(t))(1 - \gamma_i)(1 - v_i(t - R^b_i))$. Each ACK increases the congestion window by $1/w_i(t)$ or $1/(2w_i(t))$, depending on the network state. We use a random variable $\xi(t)$ to represent the increase factor. $\xi(t)$ may be either 1 or $\frac{1}{2}$. Therefore, the window $w_i(t)$ increases at the rate of $\xi(t) x_i(t - R_i(t))(1 - \gamma_i)(1 - v_i(t - R^b_i))/w_i(t)$.

On the other hand, there are $x_i(t - R_i(t))(1 - (1 - \gamma_i)(1 - v_i(t - R^b_i)))$ packet losses. Each loss drops $w_i(t)$ by $w_i(t)/2$ or $w_i(t)/5$, depending on the network state. We introduce another random variable $\eta(t)$ to represent the decrease factor. $\eta(t)$ may be either $\frac{1}{2}$ or $\frac{1}{5}$. Therefore, the window $w_i(t)$ decreases at the rate of $\eta(t) x_i(t - R_i(t))(1 - (1 - \gamma_i)(1 - v_i(t - R^b_i)))w_i(t)$. Putting the increase and decrease rate together and taking the mathematical expectation, we get the window average evolution rate,

$$\begin{aligned} \dot{w}_i(t) &= E[\xi] \frac{x_i(t - R_i(t))(1 - \gamma_i)(1 - v_i(t - R^b_i))}{w_i(t)} \\ &\quad - E[\eta] x_i(t - R_i(t))(\gamma_i + v_i(t - R^b_i)) w_i(t) \qquad (4) \end{aligned}$$

Therefore, the differential equations (2), (3), and (4) constitute the fluid-flow model of TCP Veno with RED over heterogeneous networks. It is a closed-loop system that depicts the packet-level behaviors. Note that, some other simplifying assumptions are made for the fluid-flow model. 1) We ignored the slow start and fast recovery phases in TCP Veno, because we believe that these phases have limited effects on long-run TCP performance. 2) We assumed that the loss probability is so small that the probability of having multiple losses in a round trip time is negligible.

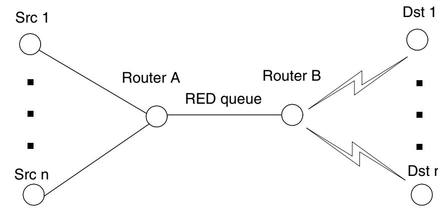

Fig. 1. The single bottleneck topology.

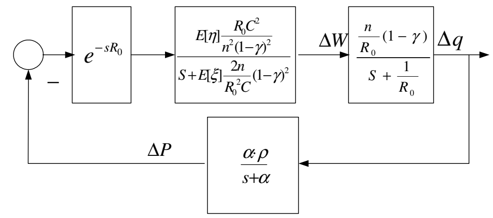

Fig. 2. Block-diagram of TCP Veno/RED feedback system.

We apply the model to the single bottleneck network as shown in Fig. 1. There are n TCP Veno flows with round trip time R. The bottleneck capacity is C. The forward delay from source to router is negligible due to high speed links. So, we have $R^f_i \approx 0$ and $R_i \approx R^b_i \approx R$. The random loss rate is $\gamma_i = \gamma$. The RED router drop probability is $p(t)$, it equals to $v_i(t)$. Assuming that $p(t)$ is small, thus $1 - p(t) \approx 1$. $w(t) \approx w(t - R)$. Therefore, equations (2) and (4) can be simplified as follows,

$$\dot{w}(t) = E[\xi] \frac{(1 - \gamma)}{R} - E[\eta] \frac{w(t)^2}{R} (\gamma + p(t - R)) \qquad (5)$$

$$\dot{q}(t) = \frac{w(t)(1 - \gamma)}{R} n - C \qquad (6)$$

The parameters $E[\xi]$ and $E[\eta]$ are the average increase and decrease factors that we introduce to describe TCP Veno window evolution in the congestion avoidance phase. The values of $E[\xi]$ and $E[\eta]$ can be computed as follows.

$$\begin{aligned} E[\xi] &= 1 \times P(N < \beta) + \frac{1}{2} \times P(N \geq \beta) \\ &= P(N < \beta) + \frac{1}{2} \times (1 - P(N < \beta)) \\ &= \frac{1}{2} + \frac{1}{2} \times P(N < \beta) \\ E[\eta] &= \frac{1}{2} - \frac{3}{10} \times P(N < \beta) \end{aligned}$$

where, $P(N < \beta)$ is the probability that Veno's estimation of N (number of backlog packets) is smaller than the threshold β. The exact value of $P(N < \beta)$ is determined by the network state distinguishing accuracy. We know $P(N < \beta) \in [0, 1]$, so $E[\xi] \in [\frac{1}{2}, 1]$ and $E[\eta] \in [\frac{1}{5}, \frac{1}{2}]$.

IV. Control Theoretic Analysis of TCP Veno/RED

In this section, we use the classical linear feedback control theory to analyze the fluid-flow model of TCP Veno with RED. Since the fluid-flow model derived in Section III is non-linear in nature, we need first convert it to a linear model. Then, we explore its relative stability margins.

A. Linear feedback control system

We first linearize the model around the equilibrium point. Denote the equilibrium point v_0, $v_0 = (w_0, q_0, p_0)$. We have $\dot{w}|_{v_0} = 0$, and $\dot{q}|_{v_0} = 0$. Therefore, we deduce that,

$$w_0^2 = \frac{E[\xi]}{E[\eta]}\frac{(1-\gamma)}{(\gamma+p_0)} \quad (7)$$

$$w_0 = \frac{R_0 C}{n(1-\gamma)} \quad (8)$$

This is the equilibrium condition. Here, $R_0 = \frac{q_0}{C} + T$, where T is the propagation delay. According to equations (5) and (6), $\dot{w} = \dot{w}(w, p, q)$ and $\dot{q} = \dot{q}(w, p, q)$. We can extend $\dot{w}$ and $\dot{q}$ at the equilibrium point v_0 using Taylor series. By ignoring the high-order powers of small values, we get the following equations,

$$\dot{w} = \dot{w}|_{v_0} + \frac{\partial \dot{w}}{\partial w}|_{v_0}\triangle w + \frac{\partial \dot{w}}{\partial q}|_{v_0}\triangle q + \frac{\partial \dot{w}}{\partial p}|_{v_0}\triangle p$$

$$\dot{q} = \dot{w}|_{v_0} + \frac{\partial \dot{q}}{\partial w}|_{v_0}\triangle w + \frac{\partial \dot{q}}{\partial q}|_{v_0}\triangle q + \frac{\partial \dot{q}}{\partial p}|_{v_0}\triangle p$$

Using the equilibrium condition (7) and (8), we deduce that,

$$\frac{\partial \dot{w}}{\partial q} = -\frac{1}{R_0^2 C}(E[\xi](1-\gamma) - E[\eta]w^2(\gamma+p_0)) = 0,$$

$$\frac{\partial \dot{w}}{\partial w} = -2E[\xi]\frac{n(1-\gamma)^2}{R_0^2 C}, \quad \frac{\partial \dot{w}}{\partial p} = -E[\eta]\frac{R_0 C^2}{n^2(1-\gamma)^2},$$

$$\frac{\partial \dot{q}}{\partial w} = \frac{(1-\gamma)}{R_0}n, \quad \frac{\partial \dot{q}}{\partial q} = -\frac{1}{R_0}, \quad \frac{\partial \dot{q}}{\partial p} = 0$$

Therefore, the linearized model is as follows,

$$\triangle\dot{w} = -2E[\xi]\frac{n(1-\gamma)^2}{R_0^2 C}\triangle w - E[\eta]\frac{R_0 C^2}{n^2(1-\gamma)^2}\triangle p(t - R_0)$$

$$\triangle\dot{q} = \frac{(1-\gamma)}{R_0}n\triangle w - \frac{1}{R_0}\triangle q$$

where $(\triangle w, \triangle q, \triangle p)$ is the small perturbation at the equilibrium point (w_0, q_0, p_0). Perform Laplace transform on the linear model and denote $L(\triangle w(t)) = W(s)$, $L(\triangle q(t)) = Q(s)$ and $L(\triangle p(t)) = P(s)$, we get the transfer functions,

$$\frac{W(s)}{P(s)} = -E[\eta]\frac{R_0 C^2}{n^2(1-\gamma)^2}\frac{e^{-sR_0}}{s + 2E[\xi]\frac{n(1-\gamma)^2}{R_0^2 C}} \quad (9)$$

$$\frac{Q(s)}{W(s)} = \frac{\frac{n(1-\gamma)}{R_0}}{s + \frac{1}{R_0}} \quad (10)$$

According to [7], RED transfer function is,

$$\frac{P(s)}{Q(s)} = \frac{\rho}{\frac{s}{\alpha}+1}$$

where, ρ and α are the same defined as in Section III. Therefore, TCP Veno with RED over heterogeneous network could be viewed as a linear feedback control system. Fig.2 shows the block-diagram of the closed-loop system. Its open-loop transfer function is,

$$G(s) = \frac{E[\eta](R_0 C)^3\rho}{2E[\xi]n^2(1-\gamma)^3} \times \frac{e^{-sR_0}}{(\frac{s}{E[\xi]\frac{2n}{R_0^2 C}(1-\gamma)^2}+1)(\frac{s}{1/R_0}+1)(\frac{s}{\alpha}+1)} \quad (11)$$

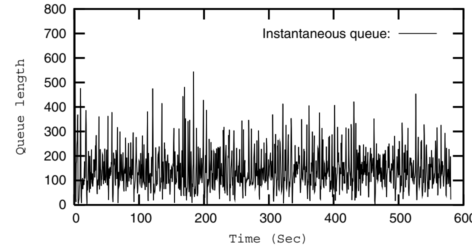

Fig. 3. Instantaneous queue of Veno/RED (loss 1%, $n = 60$), case 1.

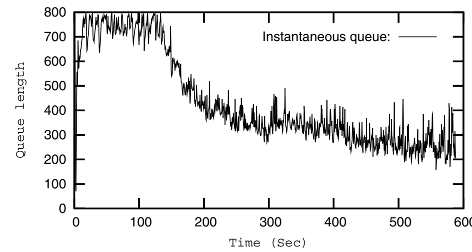

Fig. 4. Instantaneous queue of Veno/RED, case 2.

According to the open-loop transfer function and the linear feedback control theory, we arrive at the following conclusions.

1. Increase of random loss rate has negative effect on system stability. According to the equation (11), increase of random loss rate would increase the open-loop gain, and thus magnify the system perturbation.

2. Increase of link capacity or decrease of flow number has negative effect on system stability. The reason is the same as previous point, according to (11), increase of link capacity or decrease of flow number would increase the open-loop gain.

3. Increase of round trip time has negative effect on system stability. First, increase of round trip time would increase the open-loop gain. Second, increase of round trip time would increase the delay term e^{-sR_0}. The delay term is induced by $p(t - R_0)$ because TCP sender detects the packet loss one RTT after it occurs. The delay term causes system phase lag and slow response to the feedback signal.

B. Relative stability analysis

The relative stability means that, the linear feedback control system must have the ability to sustain certain negative effect before it is driven into unstable region, or the system has enough margins of safety. There are two classical stability margins to measure the system relative stability. The first one is *gain margin* and the second one is *phase margin*. The gain margin (GM) is the increase in the system gain when phase is $-180°$, and the phase margin (PM) is the amount of phase shift of the system at unity magnitude. According to the control theory, a stable system should have $GM \geq 2$ and $PM \geq 30°$. Therefore, for TCP Veno/RED system over heterogeneous networks, we have the following proposition:

Proposition:

Let ρ and α satisfy:

$$\rho_{veno} \leq \frac{2n^2(1-3\gamma)}{(R_0 C)^3}\sqrt{\frac{\omega_g^2}{\alpha^2}+1} \quad (12)$$

where $\omega_g = 0.1min\{\frac{2n}{R_0^2 C}, \frac{1}{R_0}\}$. Then the system is stable and $GM \geq 5\pi$ and $PM \geq 85°$.

Proof:

For equation (11), we have

$$G(j\omega_g) \approx \frac{E[\eta](R_0C)^3\rho}{2E[\xi]n^2(1-\gamma)^3} \cdot \frac{e^{-j\omega_g R_0}}{\frac{j\omega_g}{\alpha}+1}$$

Accordingly, $\angle G(j\omega_g) \geq -90° - 57.3\omega_g R_0 \geq -180°$. Consider γ is small, $(1-\gamma)^3 \approx (1-3\gamma)$, so we deduce,

$$|G(j\omega_g)| = \frac{E[\eta](R_0C)^3\rho}{E[\xi]2n^2(1-3\gamma)} \frac{1}{\sqrt{\frac{\omega_g^2}{\alpha^2}+1}} \leq \frac{E[\eta]}{E[\xi]} \leq 1$$

therefore, the linear feedback control system is stable, and we have seen that $\angle G(j\omega_g) \approx -95°$, so $PM \geq 85°$. To compute the gain margin, we choose $\omega = \frac{\pi}{2R_0}$. Since $\angle G(j\omega) > -180°$, then we deduce that,

$$1/|G(j\omega)| \geq \frac{E[\xi]\omega}{E[\eta]\omega_g} \geq \frac{E[\xi]}{E[\eta]} 5\pi \geq 5\pi$$

therefore, we have $GM \geq 5\pi$ and $PM \geq 85°$.

V. Simulation and validation

A. Queue dynamics of TCP Veno with RED

In this section, we use network simulator NS-2 [12] to validate our analysis. We also provide some guidelines of tuning RED parameters for improving the co-existence of TCP Veno with TFRC. The network topology is shown in Fig. 1. The side links are 100Mbps with 0.1ms delay, while the bottleneck link is 15Mbps with 10ms delay. The bottleneck router is RED. There are n flows competing on the bottleneck, in which 90% are TCP flows and 10% are TFRC flows. This is to simulate the Internet traffic that is dominated by TCP while TFRC is a relative small part. We set n to 60, so that the number of TCP flows is 54 and the number of TFRC flows is 6. The random loss rate in the wireless last-hop link is 1% with Exponential distribution. Packet size is 1000bytes and ACK is 40bytes. The simulation time is 600 seconds. The TCP flows start at 0 second, while TFRC flows join at 300 second when the queue has settled to the operating area.

The RED parameters are: $max_{th} = 250$, $min_{th} = 150$, $p_{max} = 0.1$, and queue averaging weight $\lambda = 0.0001$. Buffer size is 800. Fig. 3 shows the instantaneous queue size. We observe that the queue size oscillates in a large range. We record it as experiment case 1. Such oscillation would have negative effect on co-existing TFRC flows. Due to the RED queue oscillation, the round trip time measured by TFRC would vary in a large range, and hence cause TFRC throughput change drastically. We vary the number of flows n from 10 to 60, which means the number of TFRC flows varies from 1 to 6. For each number of flows, we compute TFRC throughput CoV, and report the average value as well as the maximum and minimum values. Fig. 6 shows the results.

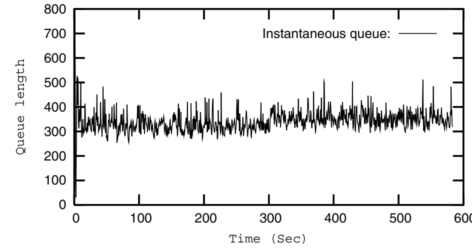

Fig. 5. Instantaneous queue of Veno/RED, case 3.

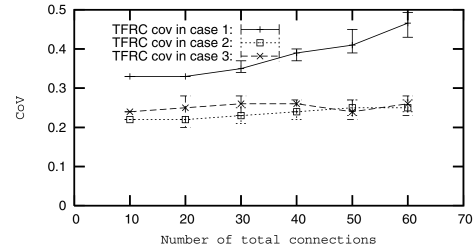

Fig. 6. CoV of TFRC in three cases.

B. Effect of RED parameters

For applications that desire smoother changes in the sending rate, the TFRC throughput fluctuation should be prevented. Based on our analysis results in Section IV, here we provide two methods of tuning RED parameters to stabilize TCP Veno/RED router queue.

Tuning RED parameters means changing the values of ρ and α. Consider equation (12), to stabilize TCP Veno/RED system, we need decrease the values of ρ, and/or α^2. Therefore, by the first method, we decrease p_{max} to 0.05 from 0.1, and λ to 10^{-6} from 10^{-4}. The total flow number n is still 60. We record it as experiment case 2. Fig. 4 shows the instantaneous queue length. We observe that the instantaneous queue is more stable than case 1. However, one disadvantage of this method is that, due to the value of λ too small, the RED queue needs a long time to settle to the operating area.

By the second method, we retain λ to 10^{-4} and p_{max} to 0.1, but increase the $[min_{th}, max_{th}]$ range to $[50, 750]$ from $[150, 250]$. We record it as experiment case 3. Fig. 5 shows the instantaneous queue length. We observe that, the queue is quite stable. Meanwhile, the disadvantage in case 2 is absent. Fig. 6 shows the CoV of TFRC in case 2 and case 3 when the flow number n varies from 10 to 60. We see that, in two cases, the values of CoV are smaller than case 1.

Fig. 7 shows the average throughput of TFRC in experiments case 1, case 2 and case 3. We plot the average throughput as well as the fairness line. The fairness line depicts the value of throughput that the TFRC flow should have if the bottleneck bandwidth is fairly shared by TCP Veno and TFRC

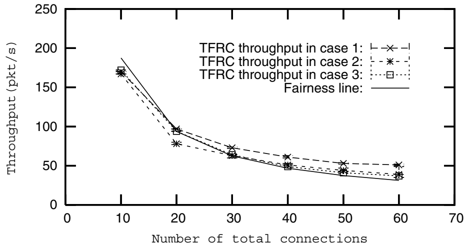

Fig. 7. Throughput of TFRC in three cases.

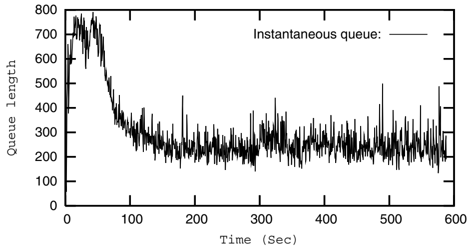

Fig. 8. Effect of increasing bandwidth.

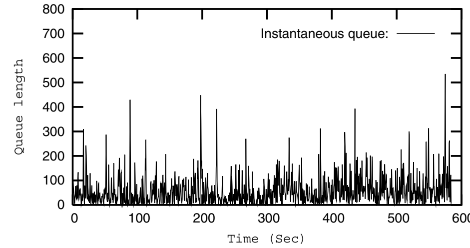

Fig. 9. Effect of increasing loss rate.

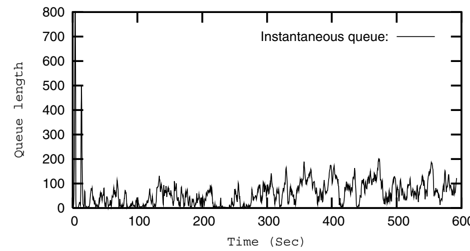

Fig. 10. Effect of increasing delay.

flows. It is calculated by the bottleneck bandwidth divided by the total number of TCP Veno and TFRC flows. We see that, in three experiment cases, TFRC throughput is always around the fairness line. This means TCP Veno and TFRC always fairly share the bottleneck bandwidth. The queue dynamics of RED does not affect their fairness.

C. *Effect of network parameters*

Now we investigate the effect of network parameters on TCP Veno/RED queue dynamics. According to our analysis, increase of bandwidth would increase the system open-loop gain, and hence cause system less stable. To validate this, we increase the bandwidth to 40Mbps from 15Mbps, while other parameters are retained the same as case 2. Fig. 8 shows the result. Compare Fig. 8 with Fig. 4, we see that the queue oscillates more. This complies with our analysis.

Second, we investigate the effect of random loss rate. According to our analysis, increase of random loss rate has negative effect on system stability. To validate this, we increase the random loss rate to 10% from 1%, while other parameters are retained the same as case 2. Fig. 9 shows the result. Compare Fig. 9 with Fig. 4, we observe that the queue oscillates drastically. Meanwhile, the queue size frequently goes down to zero. It will cause low utilization of the bottleneck bandwidth.

Finally, we investigate the effect of round trip time. According to our analysis, increase of round trip time would increase the system open-loop gain and delay term. To validate this, we increase the delay to 240ms, while other parameters are retained the same as case 2. Fig. 10 shows the result. Compare Fig. 10 with Fig. 4, we observe that, besides the queue oscillation, the queue size frequently goes down to zero, causing low utilization of the bottleneck bandwidth.

VI. Conclusion

In this paper, we studied the queue dynamics of TCP Veno with RED over wired-wireless heterogeneous networks. We first developed a fluid-flow model of TCP Veno with RED, and then used the classical linear feedback control theory to analyze it. Analysis results reveal the relationship between the RED queue oscillation and the network parameters. We used simulation tool to validate our analysis. The RED queue oscillation can have negative effect on co-existing protocols, such as TFRC. Our analysis also provided some guidelines of tuning RED parameters to stabilize router queue, and hence improve the co-existence of TCP Veno with TFRC.

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