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# A Novel AQM Scheme for Wireless Networks with BER Estimation ⋆

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**Abstract:** A novel active queue management(AQM) scheme is proposed to deal with the performance degradation of TCP in wireless scenario. One of the key sources causing performance degradation is the high bit error rate(BER), which is an intrinsic link characteristic of wireless network. A high-gain observer is constructed to estimate the effect of bit error of source data. With the estimated BER, the drop probability of queuing packets can be adapted to time-varying link conditions and network loads so that it reduces the queue oscillation and maintains good throughput. Simulation results show that the proposed scheme outperforms RED(Random Early Detection) algorithm with strong robustness to time-varying scenarios of wireless networks.

## 1. INTRODUCTION

With advantages of convenience and reduced cost over its fixed counterpart, wireless access technique enables emerging wireless applicants to access Internet with high-data-rate services. However, one of the problems is that TCP(Transmission Control Protocol) (see Jacobson [1988]) connections under such hybrid network perform poorly as TCP/AQM(Active Queue Management) is primarily designed for wired situation (Lefevre et al. [2000]).

TCP works on the transport layer and is an End-to-End protocol to control data flow injected into network. Under such a protocol, the whole network performs like a 'black box' and it is difficult for TCP source to watch inside information of network. AQM is then introduced to allow routers (nodes) to assist TCP management by actively dropping/marking packets at routers to avoid network congestion due to heavy loads (Braden et al. [2005]). However, wireless channels exhibit higher bit error rate, channel fading and frequent handoffs when taking open air as the transmission media. High bit errors damage packets and contribute to much more packet loss, and the source mistakenly takes this loss as congestion indication and unnecessarily reduces its data sending rate, which leads to low throughput and poor utilization of the network resource (Liu et al. [2006]).

Some strategies for addressing these problems have been proposed according to network types, and normally focus on modification of TCP protocols (see e.g. Brakmo et al. [1995], Akyildiz et al. [2001], Liu et al. [2001], Goff et al. [2000] and Tian et al. [2005]). However, AQM's assistance in regulating queuing under wireless scenario is rarely under consideration. Using developed dynamic model of TCP (Misra et al. [2000]), variety of AQM schemes for wired network have been studied from control theoretic viewpoint(see Misra et al. [2000], Hollot et al. [2002], Chang et al. [2006] and Feng et al. [2007]). The model is also employed in this paper to support a novel AQM design for performance enhancement in wireless channel. Paying attention to the fact that BER affects TCP source in term of undistinguished packet loss, we introduce disturbance rejection control into AQM design with high gain observer constructed to capture influence of uncertain BER on system states.

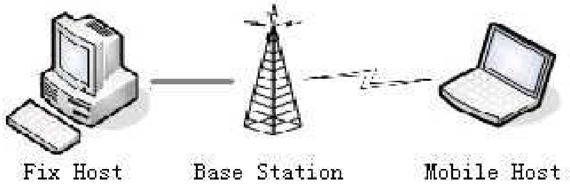


Fig. 1. Simplified wireless access network

The rest of paper is organized as follows: a TCP flow model is introduced first in Section 2, Section 3 generally describes control methodology with application to specific network examined in Section 4. Finally, simulation results are provided to demonstrate effectiveness of the proposed method.

## 2. PROBLEM FORMULATION

For better understanding the behavior of TCP, a dynamic model of TCP is developed as the following nonlinear differential equations (see Misra et al. [2000])

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$$\dot{W}(t) = \frac{1}{R(t)} - \frac{W(t)W(t-R(t))}{2R(t-R(t))}p(t-R(t)) \quad (1)$$

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

where $W$ is TCP window size, $q$ is queue length, $C$ is link capacity, $N$ is number of TCP sessions, $p$ is probability of dropped packet, $R$ is round-trip time($R = \frac{q}{C} + T_p$, $T_p$ is propagation delay).

The first term of the right side of (1) denotes that window size will increase linearly with round trip time, while the other part shows the window size decreases to half when a loss is detected. Equation (2) models increase and decrease in the queue length due to packets' arriving and leaving at routers. Simulation results using $ns$(Network Simulator) demonstrate that the above model well captures the behavior of TCP and queue dynamics(Misra et al. [2000]), which provides a good mathematical model for AQM analysis and design.

From (1), we can see that $R$ appears in the denominator in a nested form, which is difficult to cope with. Here we assume $R(t) = R_0$ as a constant according to convention. With $W_0 \gg 1$, it is also possible to ignore time-delay in TCP window size(Hollot et al. [2001]). Based on these assumptions, we take $(W, q)$ as states and $p$ as input. Given network parameters $N$, $C$, $R$, we obtain linearized TCP model by linearizing the system around its equilibrium $(W_0, q_0, p_0)$, and the relations among the operating points are $W_0^2 p_0 = 2, W_0 = \frac{R_0 C}{N}$.

$$\delta\dot{W}(t) = -\frac{2N}{R_0^2 C}\delta W(t) - \frac{R_0 C^2}{2N^2}\delta p(t-R_0) \quad (3)$$

$$\delta\dot{q}(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \quad (4)$$

where

$$\delta W := W - W_0$$
$$\delta q := q - q_0$$
$$\delta p := p - p_0$$

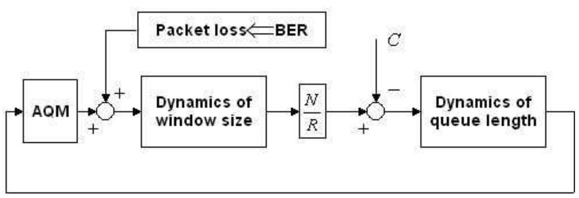


Fig. 2. Closed-loop control system

As illustrated in Fig. 2, AQM scheme is introduced with packet dropping propability as output of feedback controller to aid a TCP sender in regulating data flow injected into network. The second-order system with input time delay models the behavior of window size and queue dynamics associated with packet loss probability. Over a wireless link, since each bit error causes packet damage and triggers TCP window to decrease by half together with congestion loss induced by the router. In term of undistinguished packet loss, effects of BER in TCP transmission throughput can be considered as an input disturbance in closed-loop control system compared to system analyzed in $ns$, where an error model is added to simulate the wireless link scenario. If $B$ denotes BER, $S$ denotes packet size, the probability of packet loss caused by random bit error is expressed as

$$p_{BER} = 1 - (1-B)^S \quad (5)$$

Based on eqution (3)and (4), the transfer function of of linearized system is written as (Hollot et al. [2001]),

$$P(s) = \frac{Ke^{-sR_0}}{(s+\lambda_{TCP})(s+\lambda_{queue})} \quad (6)$$

where

$$\lambda_{TCP} = \frac{2N}{R_0^2 C}$$
$$\lambda_{queue} = \frac{1}{R_0}$$
$$K = \frac{C^2}{2N}$$

By appoximating $e^{-sR_0}$ in the transfer function using $\frac{1}{1+sR_0}$, the original system is transformed into a third order model with no input delay.

$$\delta\dddot{q}(t) = A_1\delta q(t) + A_2\delta\dot{q}(t) + A_3\delta\ddot{q}(t) + B_1(\delta p + p_{BE}) \quad (7)$$

where

$$A_1 = -\frac{2N}{R_0^4 C}$$
$$A_2 = -\frac{4N + 2R_0 C}{R_0^3 C}$$
$$A_3 = -\frac{2N + 2R_0 C}{R_0^2 C}$$
$$B_1 = \frac{C^2}{2NR_0}$$

In order to maintain stable queue length and queuing delay over a wireless link with changing BER, the control problem turns to designing an adaptive controller which can reject effects of BER on TCP window in term of input disturbances.

## 3. BER ESTIMATION AND REJECTION

With time-varying BER as unknown input disturbance, traditional AQM like RED and PI all exhibit poor ability to maintain high link utilization, here disturbance rejection control is employed to enable the system to recover from low throughput caused by random packet loss quickly. In Xia et al. [2003], auto ditrubance rejection control(ADRC) based on observer with an extended state is used to estimate unknown system parameters when input disturbances are present. This method can be applied in both nonlinear and linear systems. For our problem we employ high gain observer(Khalil [2002]) to tackle the uncertainties in the system.

### *3.1 Extended state observer*

A state observer reconstructs the state vector based on the measurement of control variable and output signal, which is significant for state feedback control especially in practice when system states are difficult to measure. For uncertain system with unknown input disturbance,

$$x^{(n)} = f(x, \cdots, x^{(n-1)}, t) + b[u(t) + w(t)] \qquad (8)$$

where $f(x, \cdots, x^{(n-1)}, t)$ can be a linear or nonlinear function, $w(t)$ is an unknown input disturbance, $u(t)$ is the control variable, $x(t), \cdots, x^{(n-1)}(t)$ are the state variables. Assuming that $x_1 = x(t), x_2 = x'(t), \cdots, x_n = x^{(n-1)}(t)$, the equation (8) is written as

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = x_3, \\ \cdots \\ \dot{x}_n = f(x, \cdots, x^{(n-1)}, t) + b[u(t) + w(t)], \\ y = x_1. \end{cases} \qquad (9)$$

With $a(t)$ denoting $f(x, \cdots, x^{(n-1)}, t) + bw(t)$ as extended state $x_{n+1}$, rewrite (9) as

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = x_3, \\ \cdots \\ \dot{x}_n = x_{n+1} + bu(t) \\ \dot{x}_{n+1} = d \\ y = x_1, \end{cases} \qquad (10)$$

where

$$d = \dot{a}(t). \qquad (11)$$

Thus, the original system is substituted by a new system of $n + 1$ order.

### 3.2 Observer gain

We design a high gain observer with extended state of (10) as

$$\begin{cases} \dot{z}_1 = z_2 + kl_1(x_1 - z_1) \\ \dot{z}_2 = z_3 + k^2 l_2(x_1 - z_1) \\ \cdots \\ \dot{z}_n = z_{n+1} + bu(t) + k^n l_n(x_1 - z_1) \\ \dot{z}_{n+1} = k^{n+1} l_{n+1}(x_1 - z_1) \end{cases} \qquad (12)$$

where $k$ is a positive real and $\mathbf{L} = [l_1 \ \ldots \ l_{n+1}]^T$ such that $\mathbf{A} + \mathbf{LC}$ is Hurwits.

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 1 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

Let $\tilde{x} = x - z$, we have

$$\dot{\tilde{\mathbf{x}}} = \mathbf{A_0}\tilde{\mathbf{x}} + \mathbf{E}d, \qquad (13)$$

where

$$\mathbf{A_0} = \begin{bmatrix} -kl_1 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -k^n l_n & 0 & \cdots & 1 \\ -k^{n+1} l_{n+1} & 0 & \cdots & 0 \end{bmatrix}, \quad \mathbf{E} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}$$

We define

$$\mathbf{e} = \text{diag}(k^n, \cdots, k, 1)\tilde{\mathbf{x}}. \qquad (14)$$

The error equation can be written as

$$\dot{\mathbf{e}} = k\mathbf{A_e}\mathbf{e} + \mathbf{E}d, \qquad (15)$$

where

$$\mathbf{A_e} = \begin{bmatrix} -l_1 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -l_n & 0 & \cdots & 1 \\ -l_{n+1} & 0 & \cdots & 0 \end{bmatrix}$$

With perturbation term $\mathbf{E}d$, a Hurwitz $\mathbf{A_e}$ may not guarantee asymptotic error convergence. However, increasing $k$ to big value can diminish effect of the perturbation part. In fact, if we define $\mathbf{V}(\mathbf{e}) = \mathbf{e^T P e}$ with $\mathbf{P}$ being a positive definite matrix satisfying $\mathbf{PA_e} + \mathbf{A_e^T P} = -\mathbf{I}$, we have

$$\dot{\mathbf{V}}(\mathbf{e}) = -\mathbf{k}\mathbf{e^T e} + \mathbf{2e^T PE}d. \qquad (16)$$

With $k$ large enough, $\dot{\mathbf{V}}(\mathbf{e})$ is negative definite in any small neighbourhood of $\mathbf{e} = \mathbf{0}$, which implies that the observer error $\mathbf{e}$ can be made arbitrarily small by using the high gain design (Ding [2005]).

### 3.3 BER rejection

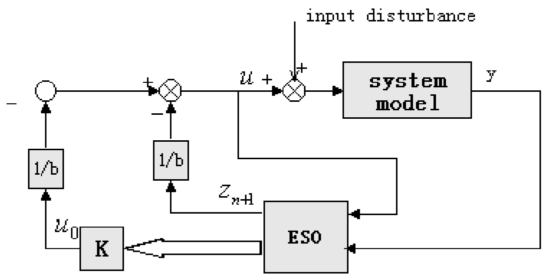


Fig. 3. Auto disturbance rejection control

With state observer properly designed and controller given by

$$u = \frac{-z_{n+1} + u_0}{b}, \qquad (17)$$

the system (10) is transformed to

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{B}u_0 \qquad (18)$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}$$

where we use state feedback control $u_0 = -\mathbf{Kz}$ based on state observer, by choosing $\mathbf{K}$ to place eigenvalues of $\mathbf{A} - \mathbf{BK}$ at desired positions. It is possible to make $\mathbf{x}$(t) approach $\mathbf{0}$ as t approach infinity.

### 3.4 Peaking Phenomenon

Assuming $a$ as constant, we have $d = 0$ and the perturbation term can be ignored. The solution of (15) contains the item like $ke^{-\lambda kt}$ with $\lambda > 0$ which exhibits impulse-like behavior as $k$ tends to infinity. This implies that initial transient of observer states have peak values before they decay rapidly towards system states whenever $x_1(0) \neq z_1(0)$, which is known as Peak Phenomenon(Khalil [2002]). When substituting feedback states by observed states, one would expect control $u$ will exhibit peaking on a short time interval and may destabilize the system. However, we can overcome the peak phenomenon simply by saturating control $u$. For system above, we have

$$u = sat(\frac{-z_{n+1} + u_0}{b}) \qquad (19)$$

## 4. AQM SCHEME AND SIMULATION RESULTS

To verify the effectiveness of the proposed approach, we use a simplified TCP/AQM network model. In Fig. 4,

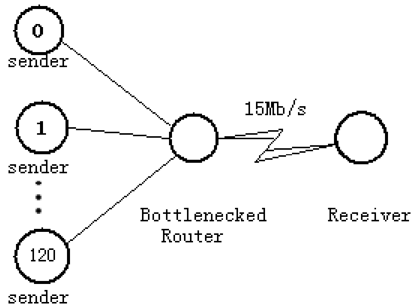


Fig. 4. Network topology

120 TCP flows are sent to receiver through a bottleneck router, wireless link is modelled using a similar BER model with random error rate distributed within $1.25 \times 10^{-7}$ and $5 \times 10^{-5}$(Liu et al. [2006]), each of which is kept for $5s$ before jumps to another. Consider the case when $q_0 = 175$ packets, $T_p = 0.2$ second and $C = 3750$ packets, which corresponds to a 15 Mb/s link with packet size 500 Bytes. For a load of $N = 120$ sessions, we have $W_0 = 7.7, p_0 = 0.034, R_0 = 0.246$. Using proposed method based on linearized system, we obtain following parameters:

$l_1 = 5.1,\ l_2 = 9.08,\ l_3 = 6.363,\ l_4 = 8$
$K = [350\ \ 120\ \ 17]$
$b = 2.3819 \times 10^5$
$k = 10$

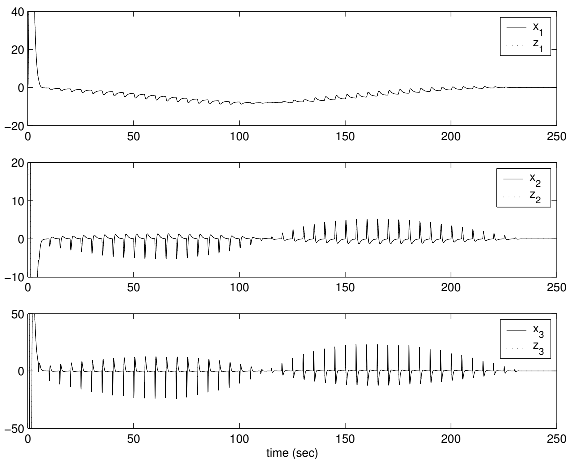


Fig. 5. States $x$ and their estimates $z$

Simulation results based on system (7) is shown in Fig. 5, Fig. 6 and Fig. 7. Fig. 5 shows that the observer is properly designed with their estimates decaying to system states so fast that effect of varying disturbance on system states can be well captured.

With extended states that track states variation due to uncertain disturbances, system can be stabilized around its operation point. Fig. 6 shows that the drop probability in ADRC is more sensitive to the variaton of BER than that in RED. This proposition makes the ADRC method compensate unnecessary decrease of window size and thus keep the queue length in a desirable level. It can also be

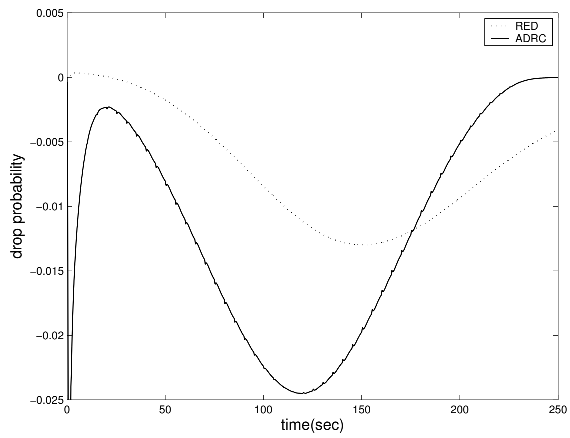


Fig. 6. Drop probability with BER

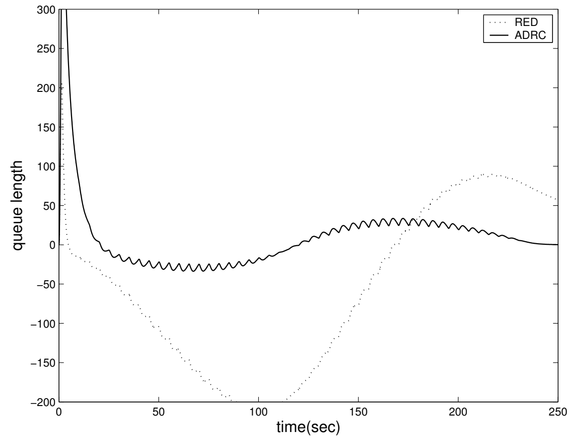


Fig. 7. Queue length with BER

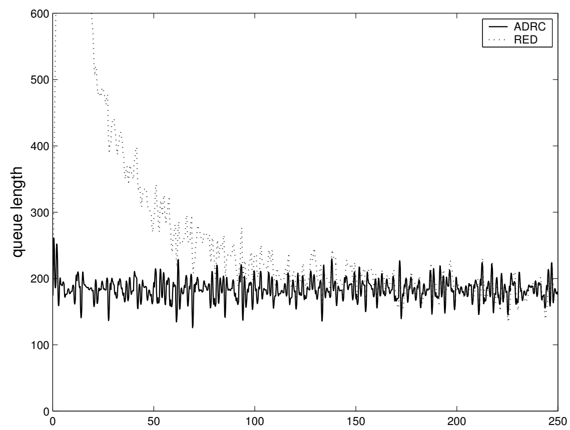


Fig. 8. Queue length under RED and ADRC in wired line

easily observed from Fig. 7 that the variation of queue length is dramatically decreased via ADRC method. We have thus demonstrated that ADRC outperforms RED under circumstance of varying disturbances.

We use the same proposed controller to conduct nonlinear system so the nonliearities of network could be captured as well. As available link bandwidth in practice is also changing with time, we take link capacity $C(t) = C + \delta C$ with a disturbance $\delta C$.

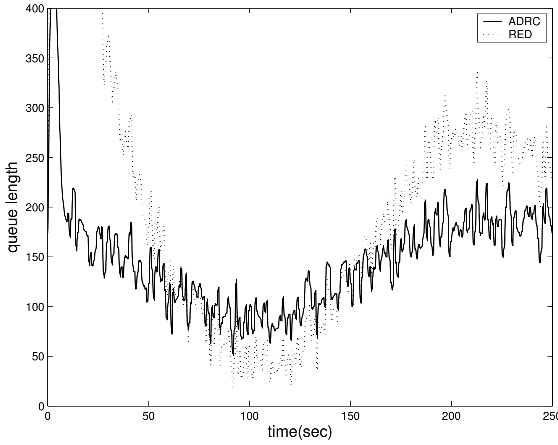


Fig. 9. Queue length in nonlinear system

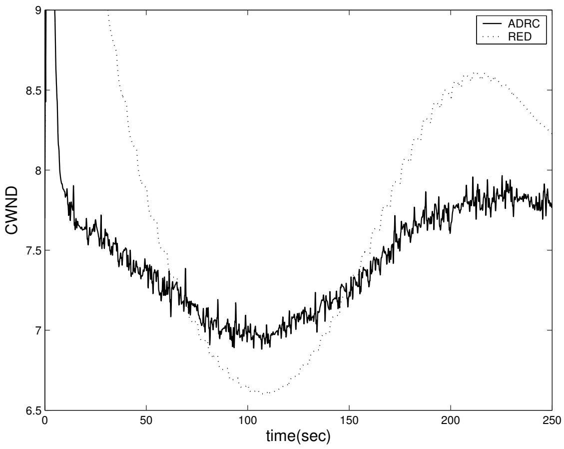


Fig. 10. CWND in nonlinear system

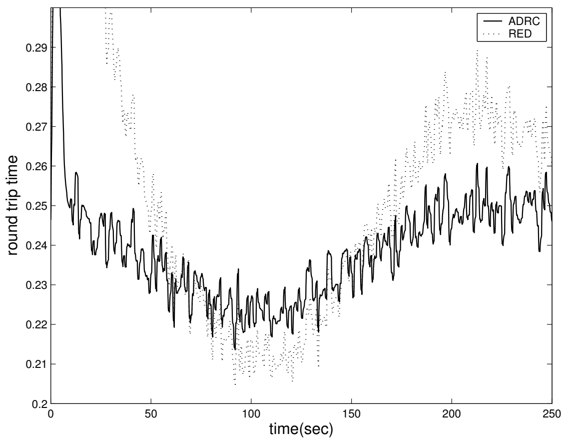


Fig. 11. Round trip time in nonlinear system

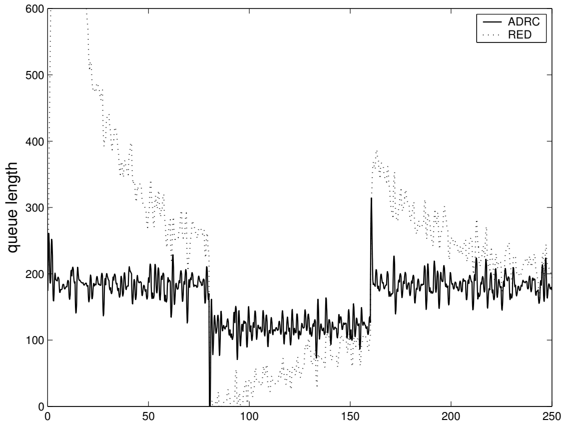


Fig. 12. Performance under varying network loads

In nonlinear system without influence of BER(Fig. 8), the quick response of queue length under ADRC is obvious. The queue length at router is regulated to operation point with much less impulse behavior when TCP flows are connected initially. The plots of the queue length, TCP window size and round-trip-time in wireless situation(Fig. 9, Fig. 10 and Fig. 11) also exhibit smaller oscillations under ADRC compared to RED scheme.

Considering queue utilization, queue overflow and emptiness should be both avoided. As shown in Fig. 12, queue length under RED may easily exhibit overflow and emptiness if channel state is poor when BER is high enough while our strategy presents a much more stable performance. Fig. 10 shows variation of congestion window size, which explains that ADRC alleviates unnecessary shrink of sauce rate to get enhanced link utilization fundamentally. The queuing delay which equals to $q/C$, indicates network's delay when together with propagation delay $T_p$. Small variation of queuing delay can be also obtained by employing ADRC instead of RED (Fig. 11).

Considering time-vary loads $N(t)$, 30 of TCP flows drop at $t = 80s$,, then reconnect at $t = 160s$, Fig. 9 shows that ADRC exhibits much more reponsive behavior and higher link utilization due to fast recovery from poor condition.

## 5. CONCLUSION

In this paper, a high gain observer and disturbance rejection control are employed to estimate BER and system variation in TCP/AQM scheme to alleviate effect of BER on network throughput. Simulation results conducted in Matlab demonstrate the effectiveness of proposed control method in wireless scenario. Over wireless network, where channel state is much more unstable due to varying condition of open environment, network routers which employ robust congestion control can assist closed-loop TCP/AQM system in avoiding queue oscillation and unnecessary waste of network resource, which implies relatively stable throughput. The proposed AQM scheme also exhibits quick response to load variation and performs better than RED in hybrid networks.

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