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Active Queue Management in Wireless Networks by Using Nonlinear Extended Network Disturbance

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Abstract: This paper studies congestion control in local wireless networks supporting transmission control protocol (TCP) under random early detection (RED). In general, congestion delays may cause instability of the routers running active queue management (AQM) protocols such as RED. Moreover, its management efficiency could be reduced by serious queue oscillation. To improve these two drawbacks, we propose a robust congestion controller focusing on the queue oscillation suppression and time-delay compensation based on an idea of nonlinear extended network disturbance (NEND). The time-delay compensation is further performed via the NEND rejection. Furthermore, the proposed strategy has been validated on NS2 showing their applicability.

1. INTRODUCTION

In recent years, active queue management (AQM) protocols are proposed based on control techniques under a fluid-flow model (Misra *et al*., 2000), capturing the dynamics of local wired networks with transmission control protocol (TCP) under random early detection (RED). For example, a PID congestion controller (Hollot *et al*., 2002) was constructed for the local wired network, a feedback congestion controller (Wang *et al*., 2002) was developed for the network running TCP combined with UDP under RED, an AQM methodology (Ariba *et al*., 2012) using a time-delay observer was established, and a self-tuning AQM mechanism (Hong *et al*., 2007) focusing on the change of TCP traffic was proposed. However, the fluid-flow system (Hollot *et al*., 2002) is only suitable for the wired case. Its extension to the wireless network running TCP with RED was addressed in the work (Zheng *et al*., 2007), in which a probability for failing data transmission was included in the model development. A robust congestion controller (Zheng *et al*., 2007) was constructed under the extended model.

Similar to the work (Zheng *et al*., 2007), some papers (Quet *et al*., 2004; Quet *et al*., 2004; Zhang *et al*., 2007; Yin *et al*., 2006) designed the robust congestion controllers corresponding to the uncertain network parameters or capacities. Furthermore, bifurcation for the congestion control strategy was studied (Raina *et al*., 2005). In the research (Zhang *et al*., 2008), locally and globally asymptotical stabilities have been discussed for a number of congestion controllers. Several kinds of system stability ensured by the congestion control have been analyzed (Peet *et al*., 2007). Globally asymptotical stability and semi-globally asymptotical stability in the congestion control were studied (Deb *et al*., 2003).

Most published works (Misra *et al*., 2000; Zheng *et al*., 2007) treated the time-delay effect as the control design constraints. Instead of this treatment, control strategies (Hsu *et al*., 2012a, b) focused on time-delay compensation by implementing either extended network disturbance (END) or nonlinear extended network disturbance (NEND). However, the controllers—consisting of the averaging queue length and window size—in previous mentioned works were all realized by taking the real parameter values as the expected ones. This inevitably causes the queue oscillation.

Motivated by the above drawback, we propose the congestion controller in terms of the queue length and window size with the objective of the time-delay compensation by performing the NEND rejection. Robust asymptotic stability of the network system adopting the proposed mechanism is discussed from the viewpoint of the real dynamics instead of its averaging behavior considered in most works (Hollot *et al*., 2002; Zheng *et al*., 2007). This gives rise to the lunching point of this paper: first network stability analysis form its real behaviour.

2. SYSTEM DEVELOPMENT AND PROBLEM DEFINITION

2.1 System Development

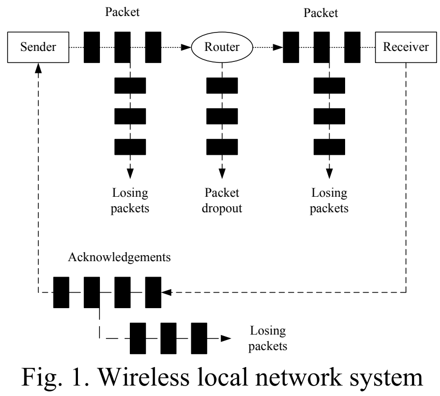

Fig. 1. Wireless local network system

The local wireless network in Fig. 1 is considered here; it includes the fixed sender sending data packets to the fixed router and fixed receiver sequentially. Acknowledgement packets are transmitted back to the sender after the receiver receives the data packets. Nevertheless, it might happen that some packets lost under a fixed losing probability during the data transmission within the channel. Moreover, there is only one connection between senders, routers, and receivers successes at the same instant. Given multiple senders/receivers, above characteristics are further formulated by the fluid-flow system (Zheng *et al.*, 2007) except for the characteristic of the single connection. Setting $P_{ul} = P_{dl} = \gamma \ll 1$ in this system yields

$$\begin{aligned} \dot{\bar{w}}(t) &= 1/\bar{R}(t) - (1-\gamma)\bar{w}(t)\bar{w}(t-\bar{R})p(t-\bar{R})/2\bar{R}(t-\bar{R}) \\ \dot{\bar{q}}(t) &= n_f \bar{w}(t)(1-\gamma)/\bar{R}(t) - C_p \end{aligned} \tag{1}$$

where the averaging round-trip time $\bar{R}(t) = a + \bar{q}/C_p$, a is the propagation delay, the dropping probability $0 \le p \le 1$, $\bar{q}/\bar{w}$ denotes the averaging queue length/window size, n_f is the number of TCP flows, and C_p is the capacity. Given $(d_{yq}, d_{yw}) \equiv (q-\bar{q}, w-\bar{w})$ with q/w being the real queue length/window size, (1) is rewritten as

$$\begin{aligned} \dot{w}(t) &= \frac{1}{\bar{R}(t)} - \frac{(1-\gamma)\bar{w}(t)\bar{w}(t-\bar{R})p(t-\bar{R})}{2\bar{R}(t-\bar{R})} + \dot{d}_{yw}(t) \\ \dot{q}(t) &= n_f \bar{w}(t)(1-\gamma)/\bar{R}(t) - C_p + \dot{d}_{yq}(t) \end{aligned} \tag{2}$$

where (d_{yw}, d_{yq}) is bounded due to the TCP definition and hardware restriction. Invariant $\bar{R}(t)$ may destabilize (2); therefore, (2) desires the time-delay compensation scheme.

2.2 Problem Statement

Despite (1) has been asymptotically stabilized by using $\Delta p \equiv K[\Delta\bar{w} \;\; \Delta\bar{q}]^T$ (Zheng *et al.*, 2007) with $(\Delta p, \Delta w, \Delta q) = (p - p_0, \bar{w} - w_0, \bar{q} - q_0)$ and $(\bar{w}, \bar{q}, p) = (w_0, q_0, p_0)$ being an equilibrium point of (1), this does not mean that (2) adopting $\Delta p \equiv K[\Delta\bar{w} \;\; \Delta\bar{q}]^T$ simultaneously holds asymptotic stability. To illustrate, consider Case (i) (Zheng *et al.*, 2007), in which $p = 0.0032(\bar{w} - w_0) + 0.000015982(\bar{q} - q_0) + p_0$ and $(w_0, q_0, p_0) = (9.2593 \text{ packets}, 500 \text{ packets}, 0.0216)$. Fig. 3 (Zheng *et al.*, 2007) illustrates that the network system implementing this controller still suffers queue oscillation. To improve this disadvantage, we must allow $\Delta p(t)$ to be more sensitive to the queue variation as $t \to \infty$. This brings a possibility to solve the considered problem that how to ensure robust asymptotic stability of (2) with respect to (d_{yw}, d_{yq}) by redesigning $\Delta p(t)$ on the basis of NEND.

3. MAIN RESULTS

Under an assumption that the ergodic hypothesis holds, the expected value of a random matrix $M(t) = [v_{mij}(t)]_{m_1 \times m_2}$ is defined as $M_m(t) = E[M(t)] \triangleq \left[\int_{t_0}^{t} v_{mij}(\tau)d\tau \big/ (t-t_0)\right]_{m_1 \times m_2}$. Moreover, $\|\cdot\|_2$ represents the induced matrix 2-norm or the 2-norm of a vector and $O/0$ denotes a zero matrix/vector.

3.1 Idea of NEND

The definition of NEND is framed by regarding the time-delay nature of (1) as induced by injecting NEND into a model without any delay. This re-describes (1) as

$$\begin{aligned} \dot{\bar{w}} &= 1/\bar{R}(t) - (1-\gamma)\bar{w}^2(t)(p - d_{nd})/2\bar{R}(t), \\ \dot{\bar{q}} &= n_f \bar{w}(t)(1-\gamma)/\bar{R}(t) - C_p, \\ y &= [w \;\; q]^T \end{aligned} \tag{3}$$

where y is the system output and d_{nd} denotes NEND. Equalizing $\dot{\bar{w}}$ in (3) and $\dot{\bar{w}}$ in (1) yields

$$d_{nd} = p - \bar{w}(t-\bar{R})p(t-\bar{R})\bar{R}(t)/\left[\bar{R}(t-\bar{R})\bar{w}(t)\right] \tag{4}$$

The value $|d_{nd}(t)|$ represents the seriousness of time-delay effect of (3). Since the TCP window size in (3) changes upon the ACK receiving rate—delayed by the data congestion, d_{nd} physically represents the effects of the data congestion on this rate. Furthermore, substituting $(\bar{q}, \bar{w}) = (q - d_{yq}, w - d_{yw})$ into (3) gives

$$\begin{aligned} \dot{w} &= f_{11}(\bar{R}_0) + f_{12}(\bar{w}_0, \bar{R}_0)p + \tilde{d}_{nd} + \dot{d}_{yw}, \\ \dot{q} &= f_a(\bar{R}_{i0})w_i - C_p - f_a(\bar{R}_0)d_{yw} + d_{est} + \dot{d}_{yq}, \\ y &= [w \;\; q]^T \end{aligned} \tag{5}$$

where

$$d_{est} = \left[f_a(\bar{R}) - f_a(\bar{R}_0)\right]\bar{w}(t) \tag{6}$$

$$\tilde{d}_{nd} = f_{11}(\bar{R}) - f_{11}(\bar{R}_0) + \left[f_{12}(\bar{w}, \bar{R}) - f_{12}(w_0, \bar{R}_0)\right]p - \breve{d}_{nd} \tag{7}$$

$\bar{R}_0 = a + q_0/C_p$, $f_{11}(t) = 1/\bar{R}(t)$, $f_{12}(t) = -(1-\gamma)\bar{w}(t)\bar{w}(t-\bar{R})/\left[2\bar{R}(t-\bar{R})\right]$, $f_a(\bar{R}) = n_f(1-\gamma)/\bar{R}$, and $\breve{d}_{nd} = f_{12}(\bar{w}(t), \bar{R}(t))d_{nd}$.

From which one has

$$\begin{aligned} \ddot{q} &= f_a(\bar{R}_0)f_{11}(\bar{R}_0) + f_a(\bar{R}_0)f_{12}(\bar{w}_0, \bar{R}_0)p \\ &\quad + f_a(\bar{R}_0)\tilde{d}_{nd} + \dot{d}_{est} + \ddot{d}_{yq} \end{aligned} \tag{8}$$

which is restated as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= f_a(\bar{R}_0)f_{11}(\bar{R}_0) + f_a(\bar{R}_0)f_{12}(\bar{w}_0, \bar{R}_0)p \\ &\quad + f_a(\bar{R}_0)\tilde{d}_{nd} + \dot{d}_{est} + \ddot{d}_{yq} \end{aligned} \tag{9}$$

with $x_1 = q$ and $x_2 = \dot{q}$.

Remark 1: In the network applications, $1 \le \bar{w}(t) \le w_{\max}$ and $1 \le \bar{q}(t) \le q_{\max}$; therefore, $d_{est}(\bar{w}, \bar{q}), \tilde{d}_{nd}(\bar{w}, \bar{q}), d_{nd}(\bar{w}, \bar{q}) \in U_2(\infty)$ based on (4) and (6) -(7) with $0 \le p \le 1$ where the continuous functions $f_{12}(\cdot)$,

$f_a(\cdot)$ and $f_{11}(\cdot)$ have finite values and $U_2(T) := \{M(t): \|M(t)\|_2 \le \varepsilon_0 \text{ over } [t_0, T]\}$. Moreover, (d_{yq}, d_{yw}) must be bounded by the TCP and hardware restriction.

Remark 2: Given $M(t) \in U_2(T)$, $\dot{M}_m(t) = [M(t) - M_m(t)]/(t - t_0)$ such that $\lim_{t\to\infty}\|\dot{M}_m(t)\|_2 \le \lim_{t\to\infty} 2\varepsilon_0/(t-t_0) = 0$, showing that $\lim_{t\to\infty} M_m(t)$ remains invariant.

Given $M(t), d(t) \in U_2(\infty)$ with the random vector $d(t) \in \mathbb{R}^{m_2}$, $\lim_{t\to\infty} E[M(t)d(t)]$ is constant from Remark 2 since $M(t)d(t) \in U_2(\infty)$. This implies $\lim_{t\to\infty} E[M(t)d(t)] \triangleq \lim_{t\to\infty} M_m(t)d_m(t) + \beta_0$ where $d_m(t) = E[d(t)]$ and β_0 is the constant vector. In other words, $E[M(t)d(t)] - M_m(t)d_m(t) - \beta_0$ is proportional to $\dot{M}_m(t)$ and $\dot{d}_m(t)$; consequently, $E[M(t)d(t)] \triangleq M_m(t)d_m(t) + \dot{M}_m(t)\Sigma_1(t) + \Sigma_2(t)\dot{d}_m(t) + \beta_0$ for any (M, d) where $\Sigma_{1,2}(t) \in U_2(\infty)$ are both differentiable at $\forall t \in [t_0, \infty)$ with appropriate dimensions. Taking this equation in $dE[M(t)d(t)]/dt = [M(t)d(t) - E[M(t)d(t)]]/(t - t_0)$ yields

$$\begin{aligned}
&\lim_{t\to\infty} dE[M(t)d(t)]/dt \\
&= \lim_{t\to\infty}\left[M(t) - \frac{\Sigma_2(t)}{t-t_0}\right]\dot{d}_m(t) + \lim_{t\to\infty}\dot{M}_m(t)\left[d_m(t) - \frac{\Sigma_1(t)}{t-t_0}\right] \\
&= M(\infty)\dot{d}_m(\infty) + \dot{M}_m(\infty)d_m(\infty)
\end{aligned} \tag{10}$$

where $d(t) = \dot{d}_m(t)(t - t_0) + d_m(t)$ and $M(t) = \dot{M}_m(t)(t - t_0) + M_m(t)$.

Remark 3: Given the constant $\lim_{t\to\infty} M_m(t) = [\bar{v}_{mij}(\infty)]_{m_1\times m_2}$ with norm-bounded $M(t_0)$, $\dot{M}_m(t) = [(v_{mij}(t) - \bar{v}_{mij}(t))/(t-t_0)]_{m\times n} = O$ indicates that $|v_{mij}(\infty) - \bar{v}_{mij}(\infty)| < \infty$ or $\dot{v}_{mij}(\infty) = \dot{\bar{v}}_{mij}(\infty) = 0$ where $\bar{v}_{mij}(t)$ is the averaging $v_{mij}(t)$. This implies $|v_{mij}(\infty)| < \infty$ such that $M(t) = [v_{mij}(t)]_{m\times n} \in U_2(\infty)$ under $\|M(t_0)\|_2 < \infty$.

Remark 4: Given $M^{(i)}(t) = [d^i v_{mij}(t)/dt^i]_{m\times n} \in U_2(\infty)$, $\lim_{t\to\infty} E[M^{(i+1)}(t)] = \lim_{t\to\infty}[M^{(i)}(t) - M^{(i)}(t_0)]/(t - t_0) = 0$, which shows $M^{(i+1)}(t) \in U_2(\infty)$ from Remark 3. After we repeats this derivation from $i = 0$ to $i = j-1$ with $j \in \mathbb{N}$, it can be concluded that $M^{(j)}(t) \in U_2(\infty)$ is available for any $j \in \mathbb{N}$ under $M(t) \in U_2(\infty)$.

3.2 Observer Design

Owing to that x_2 cannot be measured from y, we need to develop a robust observer of (9) with respect to the unknown (d_{yw}, d_{yq}). To simplify the design task, the observer is constructed under (5), which is rewritten as

$$\dot{x}_T = A_T x_T + B_T u_T + d_T,\ y_T = C_T x_T \tag{11}$$

where $x_T = [w \ \ q \ \ \tilde{d}_{nd} \ \ d_{est}]^T$, $u_T = [f_{11}(\bar{R}_0) + f_{12}(\bar{w}_0, \bar{R}_0)p \ \ -C_p]^T$, $d_T = [\dot{d}_{yw} \ \ -f_a(\bar{R}_0)d_{yw} + \dot{d}_{yq} \ \ \dot{\tilde{d}}_{nd} \ \ \dot{d}_{est}]^T$, $A_T = \begin{bmatrix} M_0 & I_2 \\ O & O\end{bmatrix}$, $M_0 = \begin{bmatrix} 0 & 0 \\ f_a(\bar{R}_0) & 0\end{bmatrix}$, $B_T = [I_2 \ \ O]^T$, and $C_T = [I_2 \ \ O]$. $d_T(t) \in U_2(\infty)$ since $\dot{d}_{yw}(t), \dot{d}_{yq}(t), \dot{\tilde{d}}_{nd}(t), \dot{d}_{est}(t) \in U_2(\infty)$ based on Remarks 1 and 4. The corresponding observer is proposed as

$$\dot{\hat{x}}_T = A_T\hat{x}_T + B_T u_T + L(t)(C_T x_T - C_T\hat{x}_T) \tag{12}$$

where $\hat{x}_T$ represents the estimation of x_T and $L(t)$ is the observer gain. Given $e_x = x_T - \hat{x}_T$, it follows

$$\dot{e}_x = A_e(t)e_x + d_T \tag{13}$$

where $A_e(t) = A_T - L(t)C_T = [v_{aij}(t)]_{4\times 4}$. Without loss of generality, the solution of (13) can be denoted by $e_x = e_m + r_x$ where $e_m(t) = E[e_x(t)]$ and $E[r_x(t)] = 0$ for all t. Robust asymptotic stability of (13) is guaranteed by letting $\lim_{t\to\infty} e_m(t) = 0$ and $\lim_{t\to\infty} r_x(t) = 0$. The former can be ensured by the result below.

Theorem 1: Consider the system (13). Suppose $\alpha_1 > 0$, $A_{em}(t) = \left[\int_{t_0}^t v_{aij}(\tau)d\tau \big/ (t-t_0)\right]_{4\times 4}$, $\tilde{A}_T(t) = \begin{bmatrix} O & I \\ \dot{A}_{em}(t) & A_e(t)\end{bmatrix}$, and $Q_1(t) = Q_1^T(t) \ge Q_2(t) = Q_2^T(t)$ for all $t \in [t_0, \infty)$. $\lim_{t\to\infty} e_m(t) = 0$ if there are $L(\cdot)$, $\tilde{A}_a(\cdot)$, $\tilde{A}_b(\cdot)$, and $P_1(\cdot) = P_1^T(\cdot) > 0$ guaranteeing

$$\tilde{A}_T(L(t)) = \tilde{A}_a(t) - \tilde{A}_b(t) \tag{14}$$

$$\tilde{A}_a^T(t)P_1(t) + P_1(t)\tilde{A}_a(t) = -Q_1(t) \tag{15}$$

$$\dot{P}_1(t) = \tilde{A}_b^T(t)P_1(t) + P_1(t)\tilde{A}_b(t) - \alpha_1 P_1^2(t) + Q_2(t) \tag{16}$$

for all $t \in [t_0, \infty)$ and $\tilde{A}_T(\infty)$ is full rank.

Proof: Expanding

$$E\left[\dot{e}_x(t)\right]=E\left[A_e(t)e_x(t)+d_T(t)\right] \tag{17}$$

at $e_x(t_0)$ gives

$$\dot{e}_m(t)=E\left[A_e(t)e_x(t)\right]+E\left[d_T(t)\right]-\frac{e_m(t)}{t-t_0}+\frac{e_x(t_0)}{t-t_0} \tag{18}$$

where $E\left[\dot{e}_x(t)\right]=\dot{e}_m(t)+\left[e_m(t)-e_x(t_0)\right]/(t-t_0)$ and $E\left[d_T(t)\right]$ becomes constant as $t\to\infty$ from Remark 2 because of $d_T(t)\in U_2(\infty)$. Performing differentiation of (18) corresponding to time derives

$$\lim_{t\to\infty}\ddot{e}_m(t)=\lim_{t\to\infty}\left\{dE\left[A_e(t)e_x(t)\right]/dt-\frac{\dot{e}_m(t)}{t-t_0}+\frac{e_m(t)}{(t-t_0)^2}\right\} \tag{19}$$

where $dE\left[A_e(t)e_x(t)\right]/dt$ in (19) is expended as (10) where $\left(M(t),d(t)\right)\triangleq\left(A_e(t),e_x(t)\right)$. Substituting this expansion into (19) yields $\lim_{t\to\infty}\dot{\tilde{x}}_m(t)=\lim_{t\to\infty}\hat{A}_T(t)\tilde{x}_m(t)$ where $\hat{A}_T(t)=\begin{bmatrix} O & I \\ \dot{A}_{em}(t)+I/(t-t_0)^2 & A_e(t)-I/(t-t_0)\end{bmatrix}\to\tilde{A}_T(t)$ as $t\to\infty$, and $\tilde{x}_m(t)=\left[e_m^T(t)\quad \dot{e}_m^T(t)\right]^T$. This shows that (17) approaches a limit system (Lee *et al.*, 2001)

$$\dot{\tilde{x}}_m(t)=\tilde{A}_T(t)\tilde{x}_m(t) \tag{20}$$

which possesses an equilibrium point $\tilde{x}_m=0$ because $\tilde{A}_T(\infty)$ has full rank.

Given $V_m(t)=\tilde{x}_m^T(t)P_1(t)\tilde{x}_m(t)$,

$$\dot{V}_m(t)=\tilde{x}_m^T(t)\left[\tilde{A}_T^T(t)P_1(t)+P_1(t)\tilde{A}_T(t)+\dot{P}_1(t)\right]\tilde{x}_m(t) \tag{21}$$

From (14)-(16) one has

$$\begin{aligned}&\dot{V}_m(t)=-\tilde{x}_m^T(t)\left[Q_1(t)-Q_2(t)\right]\tilde{x}_m(t)\\&-\alpha_1\tilde{x}_m^T(t)P_1^2(t)\tilde{x}_m(t)<0\end{aligned} \tag{22}$$

at $\forall t\in[t_0,\infty)$ where $Q_1(t)\geq Q_2(t)$ over $[t_0,\infty)$. Consequently, (17) converges to (20), which is robustly asymptotically stable. This accomplishes the proof. ■

Next, let us identify $\lim_{t\to\infty}r_x(t)$ by using the following theorem.

Theorem 2: Consider (13) featuring $\lim_{t\to\infty}e_m(t)=0$ with the determined $L(t)$. Suppose $\alpha_2>0$, $\tilde{A}_r(t)=\begin{bmatrix} O & I \\ \dot{A}_e(t)+\dot{A}_{em}(t) & A_e(t)\end{bmatrix}$ with $\tilde{A}_r(\infty)$ being full rank, $\dot{A}_e(t)\in U_2(\infty)$, $\dot{A}_{em}(t)\in U_2(\infty)$, and $Q_{r1}(t)=Q_{r1}^T(t)\geq Q_{r2}=Q_{r2}^T(t)$ for all $t\in[t_0,\infty)$. This system is robustly asymptotically stable if there are $\tilde{A}_{r1}(\cdot)$ and $P_2(\cdot)=P_2^T(\cdot)>0$ guaranteeing

$$\left[\tilde{A}_r(t)+\tilde{A}_{r1}(t)\right]^T P_2(t)+P_2(t)\left[\tilde{A}_r(t)+\tilde{A}_{r1}(t)\right]=-Q_{r1}(t) \tag{23}$$

$$\dot{P}_2(t)=\tilde{A}_{r1}^T(t)P_2(t)+P_2(t)\tilde{A}_{r1}(t)-\alpha_2P_2^2(t)+Q_{r2}(t) \tag{24}$$

for all $t\in[t_0,\infty)$.

Proof: Substituting $e_x=e_m+r_x$ into (13) gives

$$\begin{aligned}\dot{r}_x(t)&=A_e(t)r_x(t)+A_e(t)e_m(t)+\dot{e}_x(t)-A_ee_x(t)-\dot{e}_m(t)\\&=A_e(t)r_x(t)-\left[A_e(t)\dot{e}_m(t)-\ddot{e}_m(t)\right](t-t_0)+\dot{e}_m(t)\end{aligned} \tag{25}$$

where $e_m(t)=e_x(t)-\dot{e}_m(t)(t-t_0)$ and $\dot{e}_x(t)=2\dot{e}_m(t)+\ddot{e}_m(t)(t-t_0)$. That is,

$$\begin{aligned}\lim_{t\to\infty}\dot{r}_x(t)&=\lim_{t\to\infty}\left[A_e(t)r_x(t)-A_e(t)\dot{e}_m(t)(t-t_0)\right.\\&\quad\left.+\ddot{e}_m(t)(t-t_0)+\dot{e}_m(t)\right]\\&=\lim_{t\to\infty}\left\{A_e(t)r_x(t)+\left[A_e(t)-A_{em}(t)\right]e_m(t)\right\}\end{aligned} \tag{26}$$

where $\ddot{e}_m(\infty)=\dot{A}_{em}(\infty)e_m(\infty)+A_e(\infty)\dot{e}_m(\infty)$ based on (20), $\dot{e}_m(\infty)=0$, and $\dot{A}_{em}(t)=\left[A_e(t)-A_{em}(t)\right]/(t-t_0)$. Furthermore,

$$\begin{aligned}\lim_{t\to\infty}\ddot{r}_x(t)&=\lim_{t\to\infty}\left\{\dot{A}_e(t)r_x(t)+A_e(t)\dot{r}_x(t)+\left[\dot{A}_e(t)\right.\right.\\&\quad\left.\left.-\dot{A}_{em}(t)\right]e_m(t)+\left[A_e(t)-A_{em}(t)\right]\dot{e}_m(t)\right\}\\&=\lim_{t\to\infty}\left[\dot{A}_e(t)r_x(t)+A_e(t)\dot{r}_x(t)+\dot{A}_{em}(t)r_x(t)\right]\end{aligned} \tag{27}$$

with $\dot{e}_m(t)=r_x(t)/(t-t_0)$ and $\left[\dot{A}_e(\infty)-\dot{A}_{em}(\infty)\right]e_m(\infty)=0$ since $e_m(\infty)=0$ and $\dot{A}_e(t),\dot{A}_{em}(t)\in U_2(\infty)$. This gives rise to the limit system $\dot{x}_r(t)=\tilde{A}_r(t)x_r(t)$, having an equilibrium point $x_r=0$ where $x_r(t)=\left[r_x^T(t)\quad \dot{r}_x^T(t)\right]^T$ since $\tilde{A}_r(\infty)$ has full rank.

Given $V_r(t)=x_r^T(t)P_2(t)x_r(t)$ where $P_2(t)>0$ at $\forall t\in[t_0,\infty)$,

$$\begin{aligned}&\dot{V}_r(t)=-x_r^T(t)\left[Q_{r1}(t)-Q_{r2}(t)\right]x_r(t)\\&-\alpha_2x_r^T(t)P_2^2(t)x_r(t)<0\end{aligned} \tag{28}$$

from (23)-(24) and $Q_{r1}(t)\geq Q_{r2}$ at $\forall t\in[t_0,\infty)$. The dynamics (13) therefore admits $e_m(\infty)=0$ and $r_x(\infty)=0$, revealing robust asymptotic stability. ■

The observer design is completed by determining $L(t)$ in (13) to hold Theorems 1-2.

3.3 Control Design

The controller is aimed at ensuring $\lim_{t\to\infty}\left(x_1(t),x_2(t)\right)=(q_0,0)$ in (9); it is defined as

$$p\equiv\begin{bmatrix}\dfrac{-k_1(t)}{f_a(\bar{R}_0)f_{12}(w_0,\bar{R}_0)} & \dfrac{-k_2(t)}{f_a(\bar{R}_0)f_{12}(w_0,\bar{R}_0)}\end{bmatrix}\begin{bmatrix}(q-q_0)\\ \dot{\hat{q}}\end{bmatrix} \tag{29}$$

where $k_{1,2}(t)>0$ for $\forall t\in[t_0,\infty)$. The development of (29) in terms of $(q,\dot{\hat{q}})$ releases the assumption $(w,q)=(\bar{w},\bar{q})$ (Hollot *et al.*, 2002; Zheng *et al.*, 2007) in the control realization. Substituting (29) into (9) gives

$$\dot{e} = A(t)e + d_e + \begin{bmatrix} 0 & k_2(t)F_0\dot{e}_x \end{bmatrix}^T \quad (30)$$

where $e = \begin{bmatrix} e_1 & e_2 \end{bmatrix}^T$, $e_1 = q - q_0$, $e_2 = \dot{q}$, $d_e = \begin{bmatrix} 0 & f_a(\bar{R}_0)f_{11}(\bar{R}_0) + f_a(\bar{R}_0)\tilde{d}_{nd} + \dot{d}_{est} + \ddot{d}_{yq} \end{bmatrix}^T$, $A(t) = \begin{bmatrix} 0 & 1 \\ -k_1(t) & -k_2(t) \end{bmatrix}$, and $F_0 = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}$. $d_e(t) \in U_2(\infty)$ since $f_a(\bar{R}_{i0})\tilde{d}_{nd}(t) \in U_2(\infty)$ and $\dot{d}_{est}(t), \ddot{d}_{yq}(t) \in U_2(\infty)$ from Remarks 1 and 4. Combining (30), (13), and $\ddot{e}_x = \dot{A}_e(t)e_x + A_e(t)\dot{e}_x + \dot{d}_{Ti}$ (derived from (13)) gives

$$\dot{\tilde{e}} = \tilde{A}(t)\tilde{e} + \tilde{d}_e \quad (31)$$

where $\tilde{e} = \begin{bmatrix} e^T(t) & e_x^T(t) & \dot{e}_x^T(t) \end{bmatrix}^T$, $\tilde{d}_e(t) = \begin{bmatrix} d_e^T(t) & d_T^T(t) & \dot{d}_T^T(t) \end{bmatrix}^T$, and

$$\tilde{A}(t) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k_1(t) & -k_2(t) & 0 & k_2(t)F_0 \\ 0 & 0 & A_e(t) & O \\ 0 & 0 & \dot{A}_e(t) & A_e(t) \end{bmatrix}.$$

$\tilde{d}_e(t) \in U_2(\infty)$ because of $d_e(t), d_T(t), \dot{d}_T(t) \in U_2(\infty)$ based on Remark 4 and $d_T(t) \in U_2(\infty)$. Robust asymptotic stability of (31) is ensured by designing $(k_1(t), k_2(t))$ according to Theorems 1-2 with A_e substituted by $\tilde{A}$.

To satisfy $0 \le p \le 1$, we redefine

$$p \triangleq \bar{p} + u_p \quad (32)$$

where $\bar{p}(t)$ is in the form of (29) and

$$u_{pi} = \begin{cases} 1 - \bar{p}, \text{if } \bar{p} > 1 \\ 0, \quad \text{if } 0 \le p \le 1 \\ -\bar{p}, \quad \text{if } \bar{p} < 0 \end{cases}$$

Without loss of generality, we assume $\bar{p}(t) \in U_2(\infty)$ so that $u_p(t) = p(t) - \bar{p}(t) \in U_2(\infty)$. Taking (32) in (9) generates

$$\dot{\tilde{e}} = \tilde{A}(t)\tilde{e} + \tilde{d}_{eT} \quad (33)$$

where $\tilde{d}_{eT} = \tilde{d}_e + \begin{bmatrix} d_a^T & 0 & 0 \end{bmatrix}^T \in U_2(\infty)$ with $d_a = \begin{bmatrix} 0 & f_a(\bar{R}_0)f_{12}(w_0, \bar{R}_0)u_p \end{bmatrix}^T$ due to $\tilde{d}_e(t), f_a(\bar{R}_0)f_{12}(w_0, \bar{R}_0)u_p(t) \in U_2(\infty)$. The system (33) features robust asymptotic stability since it has guaranteed Theorems 1-2 with $A_e \triangleq \tilde{A}$ under the designed $(k_1(t), k_2(t))$.

4. SIMULATION

This section states a verification on NS2 with the topology in Fig. 2, in which it has a base-station BS, a wireless router n_w, FTP source routers $\overline{Src_1} - \overline{Src_{40}}$, $n_f = 40$, a destination router $\overline{Dst}$, a wired router Rr_w, the propagation delay 0.01 s, $C_p = 6$ Mbps with the packet size 500 bytes, $\gamma = 0.01$, $(w_0, q_0, p_0) = (150 \text{ packets}, 4.1667 \text{ packets}, 0.1164)$, and the activating time 0 s with the terminating time 200 s for all FTP sources. The base station supported RED while others worked under DropTail. Given the environment settings, the observer (12) was evaluated with $L(t) = \begin{bmatrix} (4t+4)I_2 & (4t^2+8t+4)I_2 \end{bmatrix}^T$. Moreover, based on Theorems 1-2, the controller (32) implemented on BS was designed with $(k_1(t), k_2(t)) = (0.1t^2, 0.1t)$.

Fig. 3 illustrates the verification results of our control strategies. In this figure, the data transmission starts after 20 s since the wireless routers could not access BS until 20 s. The queue length converges to 150 packets in Fig. 3(a), in which the queue oscillation was induced by that the fluid-flow system construction (Zheng *et al.*, 2007) did not consider that there is only one connection between senders, routers, and receivers successes at the same instant. However, this does destroy the feasibility of our method since the oscillation amplitude was less than 25 packets, which is only $25/150 = 17\%$ of q_0. Consequently, the network system was stabilized via the proposed strategy. Moreover, the error oscillations in Figs. 3(c)- 3(d) were induced by the same cause as that of the queue oscillation. This does not destroy the feasibility of the proposed manner because the estimation errors possess zero means in Fig. 3.

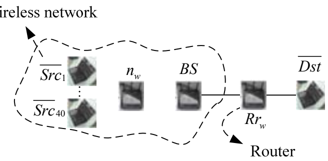

Fig. 2. Wireless network topology.

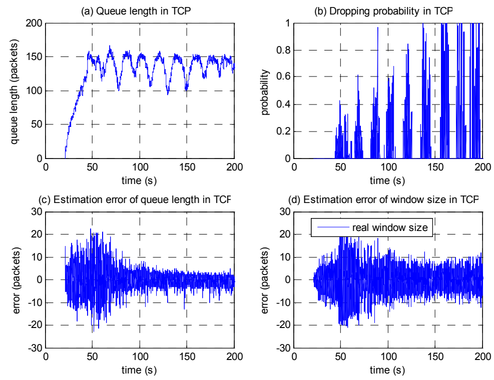

Fig. 3. Verification results, (a) queue length, (b) dropping probability, (c) queue length estimation error, and (d) window size estimation error.

5. CONCLUSION

This paper has dealt with a problem of enhancing AQM efficiency for local wireless networks with the goal of suppressing its time-delay effect based on NEND, characterizing the cause of the time-delay property. A

NEND-based solution, consisting of real the queue length and window size, has been developed for the oscillation reduction and time-delay effect suppression. The former reduction is achieved by identifying the convergence of the state's mean value while the latter is performed by the NEND rejection. Furthermore, robust asymptotic stability of the network system using the proposed controller is discussed in view of its real behavior instead of the averaging dynamics. Finally, a case study has been presented to address superiority of our method.

Not only the network dynamics but also other industrial systems feature the time-delay control problem. Applying NEND in solving their control problem gives rise to a possibility that such issues can be solved via disturbance rejection techniques. This reduces the complicity of the considered problem and further makes the control realization much easier.

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