Rate-based Feedback Control over TCP Wireless Networks Using Supervisory Control

Hee-Jung Byun and Jong-Tae Lim

***Abstract*—This paper proposes a systematic approach to the rate-based feedback control based on the supervisory control framework for discrete event systems. Since communication networks can be represented as discrete event systems, we design the supervisor to generate the admissible behavior for TCP wireless networks. It is shown that the controlled networks guarantee the fair sharing of the available bandwidth and avoid the packet loss caused by the buffer overflow of TCP wireless networks.**

***Index Terms*—Wireless TCP, supervisory control.**

I. Introduction

TRANSMISSION Control Protocol (TCP) was designed primarily for the wired networks where congestion is the main cause of the packet losses. Hence, when a wireless link forms a part of a network, the noncongestion losses may occur due to the wireless link error and TCP will half down its congestion window size unnecessarily. A number of algorithms have been proposed to improve TCP's performance over the wireless networks [1]-[8]. However, there is far less result on methods to provide fair sharing of the bandwidth. In addition, they are heuristic in nature and present the naive analyses or verifications of their methods. To deal with these problems, we present a formal method to develop a rate-based feedback control scheme over the wireless TCP networks based on the supervisory control framework [9]-[10]. This framework can effectively capture the dynamic behavior of discrete event systems and provides the existence conditions of a supervisor so that the controlled system meets a desired specification. However, there are still few control applications based on supervisory control due to its computational complexity on state space explosion. In this paper, we introduce a discrete event model of TCP networks and design an efficient supervisor to improve the wireless TCP's performance with low computational complexity.

II. Supervisory Control

We briefly describe the supervisory control framework. In the supervisory control of discrete event systems [10], the system to be controlled is modeled by an automaton $G = (\Sigma, Q, \delta, q_0, Q_m)$ where Σ is the set of events, Q is the set of states, $q_0 \in Q$ is the initial state, $Q_m \subseteq Q$ is the set of marker states, and $\delta : \Sigma \times Q \longmapsto Q$, the transition function, is a partial function defined at each state in Q for a subset of Σ. Let Σ^* denote the set of all finite strings (sequences) over Σ, including the empty string ε. A subset of Σ^* is called a language over Σ. The behavior of G is characterized by a language $L(G) := \{s \in \Sigma^* | \delta(s, q_0) \text{ is defined}\}$, which is the set of event sequences generated in G. To impose supervision on the system, we identify some of its events as controllable and the others as uncontrollable. The event set Σ is partitioned into controllable and uncontrollable events, i.e., $\Sigma = \Sigma_c \cup \Sigma_{uc}$. The controllable events in Σ_c can be disabled by a supervisor, while the uncontrollable events in Σ_{uc} are permanently enabled. A supervisor is then an agent which observes a sequence of events as it generated by G and enables or disables any of the controllable events.

Consider the wireless TCP network where the base station is the bottleneck point of the network and M TCP connections are connected to the base station. Let $X = \lceil C \rceil$ where C is the capacity of outgoing link of the base station and $\lceil x \rceil$ is the smallest integer larger than x. Assume that the feedback rate (FR) is determined by the supervisor at the base station. The feedback rate is the available bandwidth for a connection and same to all connections routed through the base station. We partition the feedback rate into $(X + 1)$ distinct elements, i.e., $FR \in \{0, 1, \cdots, X\}$.

To reflect the queue, we propose the free buffer function f_b and the value of f_b is updated every T as follows:

$$f_b = \lambda(q^0 - q) \tag{1}$$

where $0 \leq |f_b| \leq R^{dev}_{max}$, R^{dev}_{max} is the maximum increase/decrease of the feedback rate, q is the queue length of the base station, q^0 is the queue thresholds, and λ ($\lambda > 0$) is a weighting constant to be chosen. Specifically, the value of T affects both the transient response and the control overhead. The choice of the update period T can be approached as a multicriteria optimization problem and the optimal update period can be calculated [11].

Let us introduce the event set Σ, the uncontrollable event set Σ_{uc}, and the set of states Q as

$$\begin{aligned} \Sigma &= \{E_u, E_o, E_f, E^0_{JMP}, E^1_{JMP}, \cdot\cdot, E^X_{JMP}, E_{SUS}\} \\ \Sigma_{uc} &= \{E_u, E_o, E_f\} \\ Q &= \{R^0, \cdot\cdot, R^X, R^0_u, \cdot\cdot, R^X_u, R^0_o, \cdot\cdot, R^X_o, R^0_f, \cdot\cdot, R^X_f\} \end{aligned}$$

where E_u, E_o, E_f are the events representing that the value of f_b is updated and $f_b > 0$, $f_b < 0$, $f_b = 0$, respectively. Events E^i_{JMP} $(0 \leq i \leq X)$ are the events representing the increase or decrease of the feedback rate (up-transition or down-transition to state R^i). Event E_{SUS} means the maintenance of the current feedback rate. State R^i represents that the feedback rate corresponds to ith element of FR and the

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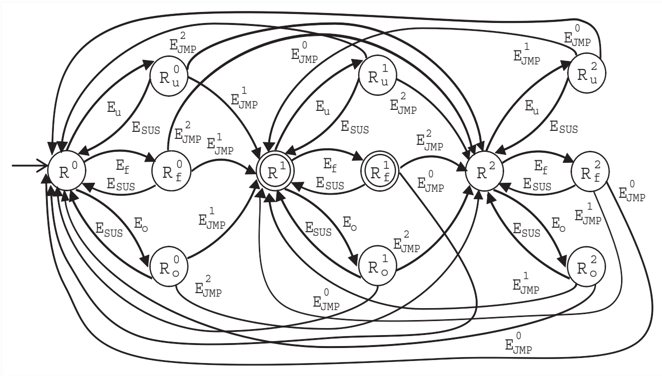

Fig. 1. State transition diagram with $X = 2, p = 1$.

value of f_b is waiting for the next update. State R_u^i, R_o^i, R_f^i represent that the feedback rate is ith element of FR, the value of f_b is updated, and $q < q^0$, $q > q^0$, $q = q^0$ respectively. Hence, an active event set at state R_u^i, R_o^i, R_f^i $(0 \leq i \leq X)$ is: $Act(R_u^i) = Act(R_o^i) = Act(R_f^i) = \{E_{SUS}, E_{JMP}^0, \cdots, E_{JMP}^{i-1}, E_{JMP}^{i+1}, \cdots, E_{JMP}^X\}$. The objectives of the proposed method are to guarantee the fair sharing and avoid the congestion-induced packet loss by keeping the queue length at the desired queue length. Therefore the marked states are R^p and R_f^p where $p = \frac{ABW}{M}$ and ABW is the available bandwidth for TCP flows at the base station. The state transition diagram with $X = 2$ and $p = 1$ is shown in Fig. 1 where the initial state is marked by an arrow and the marked states are marked by double circles.

Let us define K_d as the specification to meet our objectives. We define $S = \{E_u E_{JMP}^i, E_o E_{JMP}^j : 1 \leq i \leq X, 0 \leq j \leq X-1\}$. Then the specification K_d is described as

$$K_d = S^* \{E_f E_{SUS}\}^+ \tag{2}$$

where $\{x\}^+ = \{x\}\{x\}^*$. Note that a language $K \subset \Sigma^*$ is called *controllable* with respect to $L(G)$ if the following condition is satisfied: $\overline{K}\Sigma_{uc} \cap L(G) \subseteq \overline{K}$ [10] where $\overline{K} := \{s \in \Sigma^* | (\exists t \in \Sigma^*) st \in K\}$. Let $K_1 := \{st \in \overline{K_d} | s \in \overline{K_d}, t \in \Sigma_{uc}\}$, $s_1 \in \overline{K_d} - K_1$ and $s_2 \in K_1$. Then obviously, $s_1 t \in \overline{K_d}$ and $s_2 t \notin \overline{K_d}$ for $t \in \Sigma_{uc}$. Moreover, if the queue length becomes the queue threshold, event E_u or event E_o cannot occur as long as the network parameters do not change. As it follows from the above, since $\overline{K_d}\Sigma_{uc} \cap L(G) \subseteq \overline{K_d}$, K_d is controllable with respect to $L(G)$.

The specification K_d means that the queue length should be the queue threshold after the transient behavior represented by S^*. Since K_d is controllable, we design a supervisor to achieve K_d by choosing the appropriate feedback rate. Let $\Delta = \lceil |f_b| \rceil$. State R_u^i means that the network is under-utilized and so, the supervisor should increase the feedback rate by Δ over the current feedback rate (enable $E_{JMP}^{i+\Delta}$). On the contrary, since state R_o^i means that the network is over-utilized, the supervisor should decrease the feedback rate by Δ (enable $E_{JMP}^{i-\Delta}$). At R_f^i, the supervisor should enable E_{SUS} to hold the queue length at q^0. That is, the supervisor adapts the feedback rate according to the free buffer function so that the queue length converges to q^0. The control action of the supervisor is demonstrated in Table 1 where Σ_e :=set of enabled event and Σ_d :=set of disenabled events.

TABLE I
SUPERVISOR S

state	Σ_e	Σ_d	condition
R_u^i	$\{E_{JMP}^{i+\Delta}\}$	$Act(R_u^i) - \{E_{JMP}^{i+\Delta}\}$	$i \leq (X-\Delta)$
	$\{E_{JMP}^{X}\}$	$Act(R_u^i) - \{E_{JMP}^{X}\}$	$(X-\Delta) < i < X$
	$\{E_{SUS}\}$	$Act(R_u^i) - \{E_{SUS}\}$	$i = X$
R_o^i	$\{E_{JMP}^{i-\Delta}\}$	$Act(R_o^i) - \{E_{JMP}^{i-\Delta}\}$	$i \geq \Delta$
	$\{E_{JMP}^{0}\}$	$Act(R_o^i) - \{E_{JMP}^{0}\}$	$0 < i < \Delta$
	$\{E_{SUS}\}$	$Act(R_o^i) - \{E_{SUS}\}$	$i = 0$
R_f^i	$\{E_{SUS}\}$	$Act(R_f^i) - \{E_{SUS}\}$	-

To convey the determined rate to the source, the proposed method uses the feedback signaling scheme presented in [6]-[8], i.e., the base station writes the feedback rate determined by the supervisor in the receiver's advertised window (AWND) field carried by the TCP acknowledgements (ACKs). Since TCP sources learn about the available bandwidth independent of packet loss and consider that the packet loss occurs due to the wireless link error by avoiding the buffer overflow, there is no need to reduce the congestion window following the packet loss. Furthermore, since the supervisor determines the feedback rate with the common buffer length, the proposed method does not require maintaining per-connection state at the base station. Therefore all connections routed through the base station will receive the same feedback rate.

When the specification K_d is achieved, i.e., $q = q^0$ in the steady state, the sum of incoming window rates (r_m) to the base station equals to ABW:

$$\sum_{m=1}^{M} r_m = \sum_{m=1}^{M} FR^p = ABW$$

where FR^p is the feedback rate when $q = q^0$. Since all connections routed through the base station receive the same feedback rate, we obtain the window rate of each connection:

$$r_m = FR^p = \frac{ABW}{M}, \quad m = 1, \cdots, M \tag{3}$$

That is, if K_d is achieved, the controlled network guarantees the fair sharing of the bandwidth, avoids the congestion, and considers that the packet loss occurs due to the wireless link error by keeping the queue length at the desired queue length. Therefore, the proposed supervisor can drive the network to reach the marked states.

III. Simulation Results

We compare the proposed method with ECN (Explicit Congestion Notification) and TCP Veno [2]. TCP Veno monitors the network congestion level and uses that information to decide whether packet losses are likely to be due to congestion or random bit error. For the simulation, we divide the connections into 3 Groups, which have M_i $(1 \leq i \leq 3)$ connections respectively. The round-trip propagation time of all the connections in Group i is $(100 \cdot i)$ms. We use the following network parameters: The base station is linked to the destinations via a 10Mb/s noisy channel. The packet size is 1Kbytes, $q^0 = 30$Kbits, $T = 100$ms, and $\lambda = 1$.

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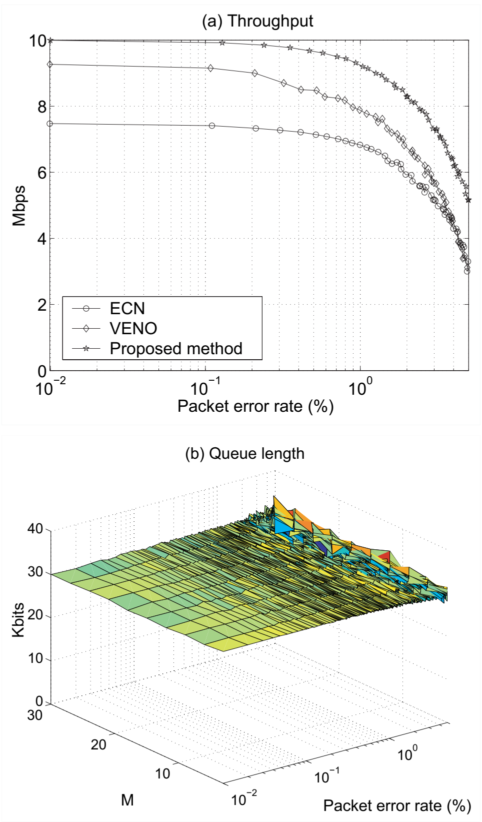

Fig. 2. Performance characteristics (a) throughput and (b) queue length.

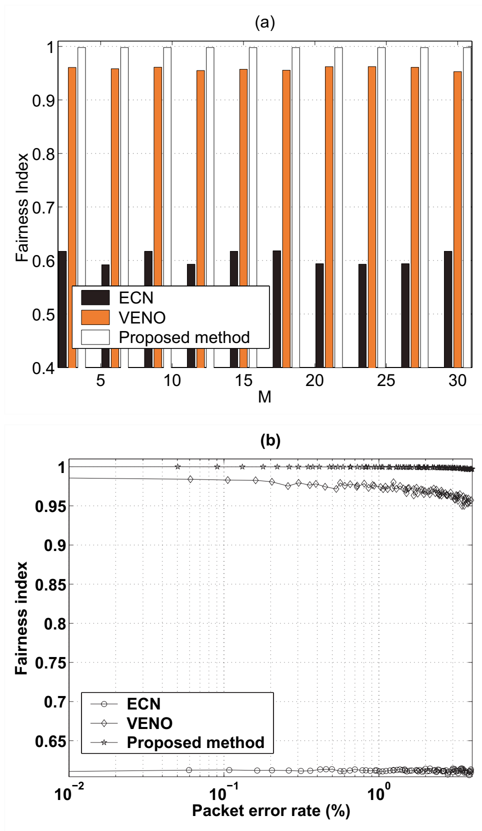

Fig. 3. Fairness index (a) vs M and (b) vs packet error rate.

Figure 2 shows the throughput with $M_1 = M_2 = M_3 = 1$ and the queue length. From Fig 2. (a), the proposed method outperforms the other TCP variants. Especially, at the high error rate, the proposed method still has satisfactory throughput whereas other TCPs experience degradation in the throughput. From Fig. 2 (b), we show that the queue length of the proposed method is stabilized around q^0 irrespective of the number of connections and packet error rate.

Figure 3 shows the fairness index [4] in the throughput. The values of fairness rage from $1/M$ to 1, with 1 corresponding to the best fair allocation among all connections. In Fig. 3 (a), we consider multiple connections (1-10 for each Group) and the packet error rate is 1%. In Fig. 3 (b), we measure the fairness index for packet error rate ranging from 0.01% to 5% with $M_1 = M_2 = M_3 = 1$. As shown in Fig. 3 (a) and (b), TCP Veno and the proposed method achieve satisfactory fairness index, but the fairness index for the proposed method is higher than TCP Veno. However, ECN does not guarantee the fair sharing of the bandwidth since the fast connections tend to get more bandwidth than the slow connections. From the above results, we conclude that the controlled network significantly improves wireless TCP performance and guarantees the fair sharing of the available bandwidth.

IV. Conclusions

In this paper we propose the discrete event system approach to accommodate the rate-based feedback control scheme and make the supervisory control feasible for the network application. From the simulations, the controlled network has revealed better performance compared with the conventional schemes.

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