FI-RED: AQM Mechanism for Improving Fairness among TCP Connections in Tandem Networks

Hiroyuki Ohsaki, Tomoya Eguchi, and Masayuki Murata
Department of Information Networking
Graduate School of Information Science and Technology, Osaka University
1-5, Yamadaoka, Suita, Osaka 565-0871, Japan
E-mail: {oosaki,t-eguti,murata}@ist.osaka-u.ac.jp

Abstract

In this paper, we focus on a tandem network, and design an AQM mechanism called FI-RED (Fairness Improvement for RED) *for improving the fairness among heterogeneous TCP connections. In FI-RED, ECN (Explicit Congestion Notification) mechanism is used for differentiating the packet marking probability of RED according to the CE (Congestion Experienced) bit of arriving packets. Namely, FI-RED suppresses congestion indication to TCP connections with a large number of hops (i.e., connections with a high probability that the CE bit is marked). With such a simple modification to the original RED, a TCP connection with a large number of hops suffers almost the same packet marking probability as one with a small number of hops. Therefore, it is expected that FI-RED improves fairness among TCP connections with different numbers of hops; i.e., bias against the number of hops. We analyze the steady state behavior of FI-RED and perform simulation experiments in several network configurations. We quantitatively show that the fairness among TCP connections is significantly improved compared with RED.*

1. Introduction

AQM mechanisms, which control the number of packets in the buffer of a router by randomly dropping arriving packets in a router, have been studied in recent years [1]. AQM mechanisms solve several problems of conventional Drop-Tail routers. For instance, by using an AQM mechanism, the average number of packets in the buffer of a router decreases, and the queuing delay at a router decreases. Hence, AQM mechanisms are expected to reduce the packet transmission delay for TCP (Transmission Control Protocol) connections.

Moreover, AQM mechanisms are expected to prevent synchronization of TCP connections caused by the buffer overflow at a router. Synchronization of TCP connections causes many continuous packet losses at the buffer of the router, and TCP significantly decreases its transmission rate due to its timeout mechanism. Hence, preventing TCP connection's synchronization is efficient for improving TCP throughput.

AQM mechanisms utilize the fact that the congestion control mechanism of TCP uses existence of packet losses in a network as feedback information from a network [2]. Namely, AQM mechanisms utilize the fact that TCP decreases its packet transmission rate in response to packet losses in a network. Considering the fact that the great portion of traffic in the current Internet is transmitted by TCP, the congestion control performed by AQM mechanisms must be very effective.

The most representative AQM mechanism is RED (Random Early Detection) [3]. RED calculates the average queue length from the current queue length (i.e., the number of packets in the buffer of a router) by using an EWMA (Exponential Weighted Moving Average). By the probability determined from the average queue length, RED randomly drops arriving packets.

For alleviating problems of RED [4, 5], several AQM mechanisms besides RED have been proposed in the literature [6-8]. However, most of those AQM mechanisms have been designed for a single router. Namely, AQM mechanisms for a network with multiple routers have not been fully investigated. When only a single router exists in a network, conventional AQM mechanisms proposed in the literature are effective for suppressing the queuing delay and for avoiding TCP throughput degradation caused by TCP connections' synchronization. Moreover, it is also possible by identifying each TCP connection at a router and using different packet dropping methods for different TCP connections, to improve fairness among TCP connections (see, e.g., FRED [4] and SRED [7]).

On the other hand, it is known that the congestion control of TCP will satisfy F_A^h fairness [9] in a tandem network where multiple routers exist in a network. This means that the TCP throughput becomes advantageous for a connection with a smaller round-trip time and/or number of hops. This fairness problem originates from the following facts: (1) the window-based flow control of TCP updates its window size every round-trip time, and (2) TCP increases/decreases its window size according to occurrence of packet losses in a network. Namely, TCP connections with a small propagation delay tend to increase their window sizes quickly, and TCP connections with a small number of hops suffer a small packet loss probability in the network.

In this paper, we focus on a tandem network with multiple routers and heterogeneous TCP connections. We design a novel AQM mechanism, called FI-RED (Fairness Improvement for RED), which operates in a tandem network and improves fairness among heterogeneous TCP connections. In FI-RED, the ECN (Explicit Congestion Notification) mechanism [10] is utilized. Specifically, FI-RED uses a different marking probability for each TCP connection according to the CE (Congestion Experienced) bit of arriving packets. Namely, FI-RED suppresses congestion indication to TCP connections with a large number of hops (i.e., connections with a high probability that the CE bit is marked). Through a simple steady state analysis and simulation experiments in several network configurations, we show that the fairness among TCP connections is significantly improved with FI-RED in a tandem network.

The organization of this paper is as follows. First, in Section 2, issues in fairness among heterogeneous TCP connections are described. In Section 3, we discuss general design goals required for an AQM mechanism. In Section 4, we explain the operation algorithm of our FI-RED, followed by discussion of its conformity to design goals. In Section 5, we show the effectiveness of FI-RED for improving fairness among heterogeneous TCP connections by a simple steady-state analysis. In Section 6, we perform simulation experiments in several network configurations and evaluate the performance of FI-RED. Finally in Section 7, we conclude this paper and discuss future works.

2. Related Works

Several researches have been performed on fairness among TCP connections. There are a large number of researches of analyzing fairness among connections of the AIMD (Additive Increase Multiplicative Decrease) flow control mechanism [11-14].

If there is no packet loss in a network, the AIMD window flow control mechanism will linearly increase its window size (the number of packets sent in a round-trip time) by α. On the contrary, when a packet loss occurs in a network, the AIMD window flow control mechanism detects a packet loss, and decreases its window size by $(1 - \beta)$. Hence, the congestion avoidance phase of TCP can be regarded as a type of AIMD congestion control mechanisms. Namely, the congestion avoidance phase of TCP is equivalent to the AIMD window flow control mechanism with $\alpha = 1$ and $\beta = 0.5$.

For instance, in [15, 9], the authors analyzed fairness among TCP connections in a tandem network. In [15], the authors assumed that all connections' round-trip times are equal, and analyzed fairness among connections running the AIMD window flow control mechanism. Consequently, the authors showed that the throughput of the AIMD window flow control mechanism converges to maximize the following function $F_A(x)$ ($F_A(x)$ fairness):

$$F_A(x) = \sum_{i=1}^{N} \log \frac{x_i}{r_0 + \nu x_i} \qquad (1)$$

where N is the number of connections, x_i is ith connection's transmission rate, r_o and ν are gains of the AIMD flow control mechanism (equivalent to α and β). In the case of TCP, Eq. (1) turns into the following equation with $r_o = 1/R$ and $\nu = 1/2$.

$$F_A(x) = \sum_{i=1}^{N} \log \frac{x_i}{\frac{1}{R} + \frac{x_i}{2}} \qquad (2)$$

where R is a TCP connection's round-trip time.

Furthermore, in [9], the authors extended the result in [15] when the round-trip times of TCP connections differ each other. Consequently, the authors showed that the throughput of the AIMD window flow control mechanism converges to maximize the following $F_A^h(x)$ ($F_A^h(x)$ fairness).

$$F_A^h(x) = \sum_{i=1}^{N} \frac{1}{R_i} \log \frac{x_i}{r_i + \nu_i x_i} \qquad (3)$$

where S is a set of connections, R_i is the round-trip time of ith connection, r_i and ν_i are ith connection's gains (equivalent to α and β in the case of AIMD). Because of $r_i = 1/R_i$ and $\nu_i = 1/2$ in the case of TCP, Eq. (3) becomes

$$F_A^h(x) = \sum_{i=1}^{N} \frac{1}{R_i} \log \frac{x_i}{\frac{1}{R_i} + \frac{x_i}{2}} \qquad (4)$$

Thus, in a tandem network, fairness among TCP connections does not satisfy Max-Min fairness [16]. Furthermore, fairness in the AIMD window flow control mechanism is analyzed in all researches explained above; only the case TCP operates in the congestion avoidance phase is analyzed. In reality, when a TCP connection's packet loss probability is large, multiple packet losses occur continuously. Consequently, a timeout mechanism is triggered, and TCP may operate in the slow-start phase. Hence, it is thought that the throughput of TCP connection with a large number of hops (i.e., TCP connections with a large packet loss probability) is degraded significantly, and fairness among TCP connections becomes worse than $F_A^h(x)$ fairness.

Note that several mechanisms which improve fairness among TCP connections in a tandem network have been proposed [17-19]. However, all of these mechanisms need to change the sender-side TCP. In reality, it is extremely difficult to change all TCP implementations since TCP has already been widely deployed in a huge number of computers.

Therefore, in this paper, we focus on improving fairness among TCP connections in a tandem network using an AQM mechanism, rather than changing TCP itself. In the following section, we first discuss design goals required for a general AQM mechanism.

3. Design Goals

In this section, we discuss design goals that a AQM mechanism should generally satisfy. In Section 4, we will explain in detail the conformity of our FI-RED to these design goals.

Consideration of TCP Congestion Control Time Scale

TCP receives ACK (ACKnowledgement) packets from the destination host, and performs congestion control based on information obtained from these ACK packets. Hence, congestion control of TCP operates on a time scale of a TCP connection's round-trip time. When designing an AQM mechanism, it is necessary to consider the time scale of such TCP congestion control. Namely, since TCP performs its congestion control on the time scale of the round-trip time, it is necessary to design the congestion control of an AQM mechanism carefully so that it may not interfere with TCP's congestion control.

For instance, we consider an AQM mechanism that exchanges control information with all other routers in a network. In this case, the propagation delay of control information becomes almost the same time scale as the TCP connection's round-trip time. Since it becomes the same time scale as TCP congestion control, it is desirable for an AQM mechanism to operate in cooperation with TCP congestion control rather than to operate independently.

Examples of congestion controls running on the same time scale as the round-trip time include ECN [10] and ICMP Source Quench [20]. On the contrary, if an AQM mechanism exchanges control information only with adjacent routers in a network, congestion control on a smaller time scale than a TCP connection's round-trip time is possible. An example of congestion controls running on a smaller time scale than a TCP connection's round-trip time is a back-pressure signaling between routers [21].

Improving Fairness among TCP Connections

Generally, in a packet-switching network, it is desirable that the bandwidth allocation satisfies Max-Min fairness [16, 22]. Max-Min fairness means maximizing the allocation of each session subject to the constraint that an incremental increase in its allocation does not cause a decrease in some other session's allocation that is already as small as its allocation or smaller. On the contrary, it is known that the bandwidth allocation to TCP connections satisfies F_A^h fairness [9]. Hence, it is desirable for AQM mechanisms to realize bandwidth allocation among TCP connections as close as Max-Min fairness.

Robustness

Since an AQM mechanism is a sort of congestion control mechanisms, it needs to have robustness against network failures. Namely, even if a network failure occurs, it is desirable for an AQM mechanism to continue its operation. Generally, it is also desirable for congestion control of an AQM mechanism to be decentralized and distributed. Since, for example, other network devices may break down, control information that an AQM mechanism uses may not arrive on time. Even in such a case, the AQM mechanism should operate without serious performance degradation.

Compatibility with Existing Network Devices

It is required that an AQM mechanism to have backward-compatibility with other existing network devices. Actually, it is unrealistic to replace all routers in the network to routers implementing a new AQM mechanism. Hence, even in environment where conventional Drop-Tail routers and/or other AQM mechanisms coexist, an AQM mechanism should operate satisfactorily. Moreover, an AQM mechanism might be gradually deployed into the existing network. Hence, when an AQM mechanism is deployed into a part of the network, the performance of the network should not be degraded. Furthermore, it is desirable to support several versions of TCP and TCP-friendly rate control mechanisms, which rely on occurrence of packet losses in the network.

4. Algorithm

In this section, the operation algorithm of our FI-RED is explained. The key idea of FI-RED is to operate RED in the ECN mode [10] (marking the CE bit of arriving packets rather than discarding them), and to distinguish every TCP connection for improving fairness among TCP connections. Specifically, FI-RED identifies every TCP connection i at a router, and estimates the packet marking probability $p_b(i)$ in upstream routers. When a packet arrives at the router, FI-RED calculates the packet marking probability p_b using the same algorithm as RED, and randomly marks the CE bit of the arriving packet with a probability given by $\max(p_b - p_b(i), 0)$.

With such a simple modification to the original RED, a TCP connection with a large number of hops suffers almost the same packet marking probability as one with a small number of hops. Therefore, it is expected that FI-RED solves unfairness among TCP connections with different numbers of hops; i.e., bias against the number of hops.

In what follows, the algorithm of FI-RED is explained in detail. FI-RED is identical to the original RED running in the ECN mode except that the packet marking probability is differentiated for every TCP connection.

1. For each packet arrival, the ECT (ECN-Capable Transport) bit [10] of the arriving packet is checked (line 8).
2. If the ECT bit is unmarked, this means that the TCP connection does not support ECN. In this case, the router operates as the normal RED. On the contrary, the router operates using the following algorithm (lines 8–10).
3. Based on sender/receiver IP addresses and sender/receiver port numbers, each TCP connection is identified. In what follows, the identifier of the TCP connection is denoted by i.
4. For the TCP connection i, the probability that the CE bit is marked in upstream routers, $p_c(i)$, is estimated using EWMA (Exponential Weighted Moving Average) (line 10). Specifically, $p_c(i)$ is updated as

$$p_c(i) \quad \leftarrow \quad (1-\nu) \times p_c(i) + \nu \times CE \qquad (5)$$

   where ν is a control parameter (i.e., the weight of EWMA) and CE is the value of the CE bit of the arriving packet.
5. Using the estimated probability $p_c(i)$, the packet marking probability of the TCP connection i in upstream routers, $p_b(i)$, is estimated as follows. In the original RED, when the packet marking probability is p_b, the packet drop probability p for all arriving packets is given by [3]

$$p \quad = \quad \frac{2\,p_b}{1+p_b} \qquad (6)$$

   By deriving the inverse function of Eq. (6), the packet marking probability for the TCP connection i in upstream routers, $p_b(i)$, is obtained as (line 11)

$$p_b(i) \quad = \quad \frac{p_c(i)}{2-p_c(i)} \qquad (7)$$

   Note that every upstream router might be Drop-Tail, RED, or other AQM routers. Hence, $p_b(i)$ is *an imaginary packet marking probability of a single RED router*, which is an aggregation of all upstream routers. Namely, $p_b(i)$ is equivalent to the packet marking probability of a single RED router that marks the CE bit of arriving packets with a probability $p_c(i)$.
6. Similar to the original RED, the packet marking probability p_b is determined from the average queue length (line 15).
7. If the ECT bit is marked, the CE bit of the arriving packet is randomly marked with a probability $\max(p_b(i) - p_b)$ (line 17).

In what follows, we discuss conformity of FI-RED to our design goals explained in Section 3.

Consideration of TCP Congestion Control Time Scale

Since FI-RED uses a low-pass filter for averaging its queue length, the time scale of its control is larger than a TCP connections' round-trip time. Hence, it is expected that FI-RED does not interfere with TCP's congestion control.

Improving Fairness among TCP Connections

FI-RED improves fairness among TCP connections in a tandem network. In the original RED, a TCP connection with the large number of hops has a large probability that the CE bit is marked. Consequently, fairness among TCP connections is degraded. FI-RED allows a TCP connection with a larger number of hops to gain more bandwidth by marking a CE bit less frequently. However, the problem that a TCP connection's throughput is dependent on its round-trip time is not solved.

For instance, a mechanism of measuring a round-trip time at the router and changing the packet marking probability according to the measured round-trip time might solve this problem. However, variation of TCP connection's round-trip times is generally large, and exact measurement of the round-trip time at the router is difficult. Furthermore, since the routing in the Internet is not necessarily symmetric, it is sometimes impossible to measure a TCP connection's round-trip time at the router.

Therefore, it is difficult for AQM mechanisms to accurately measure a TCP connection's round-trip time. The problem that the TCP throughput is dependent on its round-trip time originates from the fact that the control frequency of TCP is every round-trip time. Since this is an essential problem in TCP, we believe that solving this problem by an AQM mechanism is impractical. In this paper, we therefore do not deal with the unfairness issue among TCP connections with different round-trip times.

Robustness

FI-RED just utilizes information of the CE bit of arriving packets, which might be marked by upstream routers. If the ECT bit of the arriving packet is unmarked, FI-RED operates as the original RED. Hence, FI-RED is able to coexist with other conventional routers such as Drop-Tail routers and other AQM mechanisms. Note that, it is expected that if more FI routers-RED are introduced in the network, fairness among TCP connections is more improved. We believe

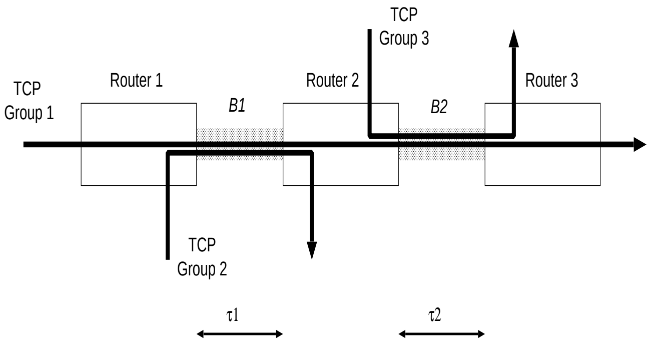

Figure 1. Analytic model

this fact can be incentive for introducing the ECN mechanism in the network.

Compatibility with Existing Network Devices

Since FI-RED only utilizes the ECN mechanism (i.e., ECT and CE bits in the IP header), it can be used with arbitrary transport-layer protocols supporting ECN. When a transport-layer protocol does not support ECN (i.e., when the ECT bit is unmarked), FI-RED operates as same as the original RED. Therefore, it is possible to deploy FI-RED into a part of routers in the network. If FI-RED is deployed into all routers in the network, it is expected that the fairness among TCP connections is further improved.

In addition, since FI-RED uses the fundamentally same algorithm as RED, many research results on RED can be directly applied without change. It is also possible to use approaches like SRED [7] and FRED [4] for further improving fairness among TCP connections accommodated at the same router.

5. Analysis

In this section, using a simple steady state analysis, we evaluate FI-RED and show how fairness among TCP connections is improved.

Our analytic model is shown in Fig. 1. The analytic model consists of three routers (routers 1–3) and three groups of TCP connections (TCP groups 1–3). TCP group 1 has connections with 2 hops from the router 1 to the router 3. TCP groups 2 and 3 have connections with 1 hop from the router 2 to the router 3, and from the router 1 to the router 2, respectively. The number of connections in TCP group i is denoted by N_i.

Let B_j denote the link bandwidth of the router j ($1 \leq j \leq 3$), and q_j^* the average queue length in steady state of the router j. Propagation delays of links between routers 1 and 2 and between routers 2 and 3 are denoted by τ_1 and τ_2, respectively. We assume that all bandwidth of access links between a TCP source host and a router, and between a TCP destination host and a router are sufficiently larger than the link bandwidth of routers, B_j. We assume that all propagation delays of access links are negligible. We also assume that all TCP connections always have data to transmit.

It is known that TCP throughput in steady state is approximately given by [23]

$$T(R,p) \simeq \frac{1}{R}\sqrt{\frac{3}{2p}} \qquad (8)$$

where R is a TCP connection's round-trip time, and p is a packet loss probability in the network or a packet marking probability of the CE bit in the IP header. Note that although more detailed formula of TCP throughput is derived in [23], we use Eq. (8) for illustrative purposes.

In steady state, probability that the CE bit of arriving packets at the router j is 1 (CE bit marking probability) is denoted by p_j. First, we focus on the case with RED routers. In the case of RED, routers 1 and router 2 independently mark the CE bit of arriving packets, the probability $p_{1,2}$ that the CE bit of packets in TCP group 1 is marked is given by the following equation.

$$p_{1,2} = 1 - \Pi_{j=1}^{2}(1-p_j) \qquad (9)$$

On the contrary, in the case of FI-RED, the probability $p_{1,2}$ that the CE bit of packets in TCP group 1 is marked in steady state is given by

$$p_{1,2} = \max(p_1, p_2) \qquad (10)$$

Let T_i be each connection's throughput in TCP group i. The following relations are obtained by approximating the round-trip time R_i of TCP group i by the sum of the queuing delay in the router and the propagation delay of the link.

$$T_1 = T(R_1, p_{1,2}) \simeq T(R_1, \sum_{j=1}^{2} p_j) \qquad (11)$$

$$T_2 = T(R_2, p_1) \qquad (12)$$

$$T_3 = T(R_3, p_2) \qquad (13)$$

$$R_1 = \sum_{j=1}^{2}\left(2\tau_j + \frac{q_j^*}{B_j}\right) \qquad (14)$$

$$R_2 = 2\tau_1 + \frac{q_1^*}{B_1} \qquad (15)$$

$$R_3 = 2\tau_2 + \frac{q_2^*}{B_2} \qquad (16)$$

In the network shown in Fig. 1, the link bandwidth B_j of the router and TCP connection's throughput become identical in steady state. Thus, the following relations are obtained.

$$N_1 T_1 + N_2 T_2 = \frac{B_1}{1-p_1} \qquad (17)$$

$$N_1 T_1 + N_3 T_3 = \frac{B_2}{1-p_2} \qquad (18)$$

	p_1	p_2	T_1	T_2	T_3
RED	0.014	0.014	0.265	0.749	0.749
FI-RED	0.017	0.017	0.339	0.678	0.678

Table 1. CE bit marking probability and TCP throughput ($B_1 = B_2 = 0.2$ [packet/ms], $\tau_1 = \tau_2 = 10$ [ms])

	p_1	p_2	T_1	T_2	T_3
RED	0.008	0.008	0.263	0.745	0.745
FI-RED	0.010	0.010	0.337	0.674	0.674

Table 2. CE bit marking probability and TCP throughput ($B_1 = B_2 = 0.4$ [packet/ms], $\tau_1 = \tau_2 = 10$ [ms])

TCP connection's throughput in steady state can be derived by solving the above equations for p_1 and p_2.

In what follows, we present some numerical examples, and show how fairness among TCP connections is improved using FI-RED as compared with RED. In numerical examples, the following parameters are used; $N_1 = 1$, $N_2 = 1$, $N_3 = 1$, and the average queue length of the router is $q_1^* = q_2^* = 10$ [packet].

Numerical results of our steady state analysis, when the link bandwidth B_j of the router and the propagation delay τ_j of the link are changed, are shown in Table 1 through Table 3. These tables show the CE bit marking probability p_j and the TCP throughput T_i in steady state. Focusing on the CE bit marking probability p_j, one can find that the value of FI-RED is larger than that of RED. This is because packets in TCP group 1 are less likely to be marked at the latter FI-RED router, router 2, so that the throughput of TCP group 1 becomes larger.

We next focus on the fairness among TCP connections. In what follows, the ratio of TCP connection's throughput (T_2/T_1 and T_3/T_1) will be used as the fairness index. In RED, the ratio of TCP connection's throughput is $T_2/T_1 = T_3/T_1 = 2.83$, regardless of the link bandwidth B_j of the router and the propagation delay τ_j of the link.

On the contrary, in FI-RED, the ratio of TCP connection's throughput is $T_2/T_1 = T_3/T_1 = 2.0$. Note that the fairness index would be $T_2/T_1 = T_3/T_1 = 1.0$ if Max-Min fairness is satisfied. From these observations, it can be found that with FI-RED, the fairness among TCP connections is improved about 30% as compared with the case of RED.

	p_1	p_2	T_1	T_2	T_3
RED	0.008	0.008	0.263	0.745	0.745
FI-RED	0.010	0.010	0.337	0.674	0.674

Table 3. CE bit marking probability and TCP throughput ($B_1 = B_2 = 0.2$ [packet/ms], $\tau_1 = \tau_2 = 20$ [ms])

In RED, TCP group 1 of a larger number of hop suffers a larger CE bit marking probability than TCP groups 2 and 3 of a smaller number of hops. Therefore, the throughput of TCP group 1 becomes smaller than that of TCP groups 2 and 3. On the contrary, the CE bit marking probability of TCP group 1 becomes small with FI-RED. Consequently, the throughput of TCP group 1 becomes larger than that with RED and therefore the fairness among TCP connections is improved.

6. Simulation

In this section, through simulation experiments, we quantitatively show how fairness among TCP connections is improved by introducing FI-RED. We performed simulations by changing system parameters (i.e., the link bandwidth, the number of routers, the number of TCP connections) and the control parameter ν of FI-RED. We compare performance of FI-RED with that of the original RED; as discussed in Section 1, other AQM mechanisms such as FRED and SRED are designed to improve fairness among TCP connections accommodated at a single router.

The network topology used for our simulation is shown in Fig. 2. This network topology consists of N routers and $N-1$ groups of TCP connections. The source and destination hosts belonging to TCP group i ($1 \leq i \leq N$) are S_i and D_i in the figure, respectively. Simulations were performed by setting the number of TCP connections that constitutes TCP group i to $N_i = 1$ or $N_i = 10$. Fairness among greedy TCP connections is of great importance, since for AQM mechanisms, short-lived TCP connections can be viewed as background traffic. Hence, in our simulation, all TCP connections performed data transfer continuously, and all TCP connections' packet length was fixed at 1,000 [byte]. Hence, in this network topology, all links between routers are bottlenecks.

Bandwidth of all links between routers were uniquely set to $B = 2$ or $B = 10$ [Mbit/s], and their propagation delays were fixed at $\tau = 10$ [ms]. Bandwidth of all links between a source host and a router and between a destination host and a router were set to 100 [Mbit/s], and their propagation delays were set to 0 [s]. The control parameters of RED were set to $w_q = 0.0025$, $min_{th} = B\,\tau/2$, $max_{th} = 3\,min_{th}$, and $max_p = 0.1$. Moreover, the buffer size of RED router was set to $3max_{th}$. For simulation, ns-2 [24] simulator (version 2.26) was used.

To evaluate the effectiveness of FI-RED, the fairness in-

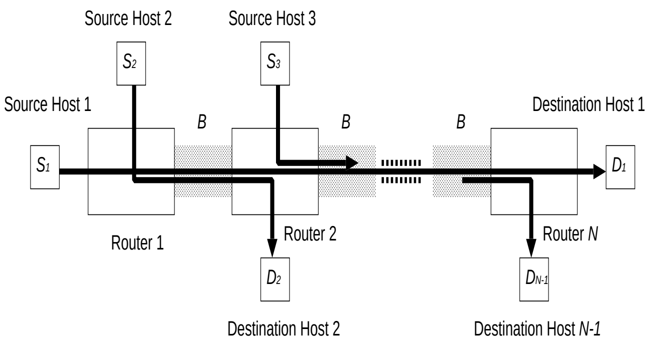

Figure 2. Network topology used for simulation

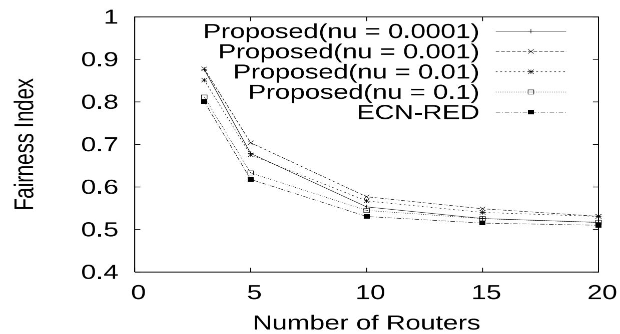

Figure 4. Fairness index F for different numbers of routers ($B = 2$ [Mbit/s] and $N_i = 1$)

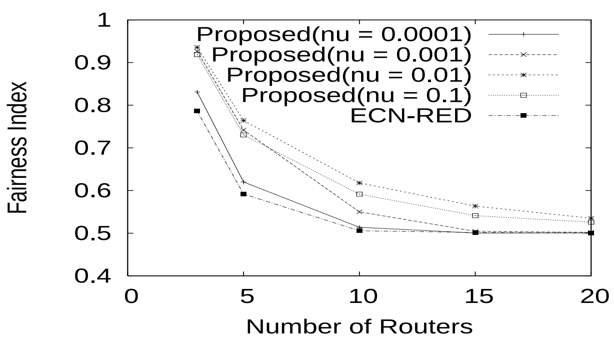

Figure 3. Fairness index F for different numbers of routers ($B = 2$ [Mbit/s] and $N_i = 10$)

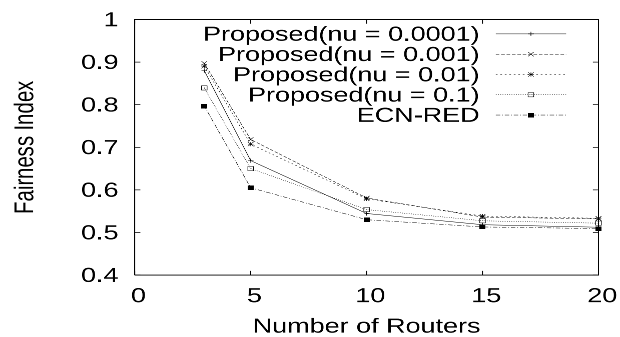

Figure 5. Fairness index F for different numbers of routers ($B = 10$ [Mbit/s] and $N_i = 10$)

dex defined by the following equation is used [25].

$$F = \frac{(\sum_{i=1}^{M} x_i)^2}{M \sum_{i=1}^{M} {x_i}^2} \quad (19)$$

where M is the number of TCP connections that passes through the bottleneck link, and x_i is the throughput of i-th TCP connection that passes through the bottleneck link. A larger fairness index F means more fair bandwidth allocation to TCP connections.

The fairness index F for different numbers of routers N and control parameters ν of FI-RED are shown in Fig. 3 ($B = 2$ and $N_i = 10$), Fig. 4 ($B = 2$ and $N_i = 1$), and Fig. 5 ($B = 10$ and $N_i = 10$). In these figures, simulation results with RED operating in the ECN mode are also included for comparison purposes.

First, Fig. 3 indicates that FI-RED can achieve better fairness than RED operating in the ECN mode. This tendency appears notably, in particular, when the number N of routers is small. For instance, when the number of routers is $N = 3$, the fairness index of RED is about 0.79, whereas that of FI-RED is 0.94 for $\nu = 0.01$.

However, effectiveness of FI-RED is dependent on a configuration of the control parameter ν. In Fig. 3, the fairness index takes the largest value when $\nu = 0.1$. On the contrary, the fairness index takes the smallest value when $\nu = 0.0001$. However, it should be noted that even in the worst case, FI-RED achieves better fairness than RED.

Let us focus on the cases when the number of TCP connections in each group is $N_i = 1$ (Fig. 4), and when the link bandwidth between routers is $B = 10$ [Mbit/s] (Fig. 5). One can find that FI-RED achieves better fairness than RED in all cases. In particular, it should be noted that the fairness index shows the maximum value when $\nu = 0.01$. This means that the optimal configuration of the control parameter ν is hardly dependent on the link bandwidth between routers and the numbers of TCP connections.

From these observations, we conclude that FI-RED achieved better fairness among heterogeneous TCP connections as compared with RED. Moreover, we find that the optimal configuration of the control parameter ν of FI-RED is not dependent on the number of TCP connections or the link bandwidth between routers.

7. Conclusion

In this paper, we have discussed general design goals required for an AQM mechanism. We have designed a novel AQM mechanism, called FI-RED, which operates in a tandem network and improves fairness among heterogeneous TCP connections. By suppressing congestion indication to TCP connections traversing congested routers, FI-RED improves fairness among TCP connections with different numbers of hops. Through a steady state analysis and simulation experiments, we have shown that FI-RED significantly improves fairness among heterogeneous TCP connections in a tandem network.

In this paper, we have designed an AQM mechanism that utilizes the ECN mechanism for improving fairness among heterogeneous TCP connections with different numbers of hops. However, as we have discussed in Section 4, even with FI-RED, the unfairness caused by the difference in TCP connection's round-trip times is difficult to solve. As future work, we need to investigate an approach for improving the unfairness among TCP connections with different round-trip times. Also, investigation of interference of FI-RED with non-standard TCP protocols, such as TCP Vegas, TCP Westwood, HighSpeed TCP and FAST TCP, would be interesting.

Other important future work should cover scalability issues of FI-RED. FI-RED maintains internal variables for every TCP connection to change the packet marking probability. Therefore, the maximum number of TCP connections accommodated in the router is restricted by the memory size/processing speed of the router. Hence, we need to address scalability issue of FI-RED, and investigate possible solutions.

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