Performance Analysis of REDP Marker with a combined Dropper for improving TCP Fairness of Assured Services

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ABSTRACT

To provide the end-to-end service differentiation for assured services, the random early demotion and promotion (REDP) marker in the edge router at each domain boundary monitors the aggregate flow of the incoming in-profile packets and demotes in-profile packets or promotes the previously demoted in-profile packets at the aggregate flow level according to the negotiated interdomain service level agreement (SLA). The REDP marker achieves UDP fairness in demoting and promoting packets through random and early marking decisions on packets. But, TCP fairness of the REDP marker is not obvious as for UDP sources. In this paper, to improve TCP fairness of the REDP marker, we combine a dropper with the REDP marker. To make packet transmission rates of TCP flows more fair, at the aggregate flow level the combined dropper drops incoming excessive in-profile packets randomly with a constant probability when the token level in the leaky bucket stays in demotion region without incoming demoted in-profile packets. It performs a dropping in the demotion at a domain boundary only if there is no prior demotion. The concatenate dropping at multiple domains is avoided to manifest the effect of a dropping at a domain boundary on TCP fairness. We experiment with the REDP marker with the combined dropper using ns2 simulator for TCP sources. The simulation results show that the REDP marker with the combined dropper improves TCP fairness in demoting and promoting packets by generating fair demoted in-profile traffic compared to the REDP marker. The effectiveness of the selected drop probability is also investigated with showing its impact on the performance of the REDP marker with the combined dropper.

Keyword : QoS, DiffServ, Assured Services, TCP, Fairness

I. INTRODUCTION

With the proliferation of multimedia and real time applications, it is becoming more desirable to provide certain quality of service (QoS) guarantee for Internet applications. The Differentiated Services (DiffServ) architecture has been proposed as a scalable way of providing QoS in the Internet [1]. Scalability is achieved by moving complicated functionalities such as Per-flow or flow aggregate marking, shaping, and policing toward the edge router and leaving the core router with very simple functionality. With DiffServ, packets are marked at the ingressive edge router of the network with a DiffServ codepoint (DSCP) [2] and at the core router they are given a forwarding treatment according to their DSCP. Each DSCP corresponds to a Per-Hop Behavior (PHB). DiffServ provides packet level service differentiation through simple and predefined PHBs. Currently, the IETF has defined one class for Expedited Forwarding (EF) PHB [3] and four classes for Assured Forwarding (AF) PHB [4].

An Internet connection can span through a path involving one or more network domains. If we want to guarantee the end-to-end minimum throughput of the connection, we have to make sure that the aggregate traffic along the path does not exceed any of the interdomain negotiated

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service level agreements (e.g., the traffic rate) after this flow joins. This is very hard to ensure since the interdomain service level agreement (SLA) is not usually renegotiated at the initiation of each new connection. For assured services, the interdomain traffic rates are usually negotiated statically based on statistical estimation or updated periodically to avoid signaling overhead and scalability problem. So, the instantaneous aggregate in-profile traffic rate may be higher or lower than the negotiated rate determined by interdomain SLA [5].

To provide the end-to-end service differentiation in DiffServ model, it is needed to extend the per-hop behavior over multiple network domains. Then, in the case of higher incoming aggregate in-profile traffic rate, the intermediate marker in the edge router demotes some of the "in" packets to "out" so that the aggregate rate of "in" packets conform to the negotiated rate. The initial marking of packets at host markers can be done on a per-flow basis. But in order to implement the per-flow marking in a intermediate marker, all the intermediate markers should know the original contracted rate of each flow and tokens assigned to each flow should be proportional to its original contracted rate. So, the per-flow marking in the intermediate marker needs per-flow monitoring and signalling where scalability problem occurs. Then, the intermediate marking must be done on the aggregate flow level for the ease of scalability. Furthermore, the demotion, although exercised at the aggregate flow level, should affect all the connections proportionally to their current usage (i.e. fair demotion). On the other hand, if the incoming aggregate in-profile traffic rate is lower, ideally the intermediate marker should promote a "previously demoted" packet to reallocate the excess capacity. This promotion should be fair across all connections as well.

In the random early demotion and promotion (REDP) marker for assured services, identification of a previously demoted "in" packet is ensured using the AF PHB specified packet markings. In order to support this, the REDP intermediate marker in the edge router uses a three-color (red, yellow, and green) marking process [4], where yellow is used as an indicator for temporary demotion. In promoting packets, it provides better assured services than the two-color promotion through the tricolor promotion [5]. It uses two AF classes to isolate UDP and TCP traffics. The REDP marker was proposed to remove the phase effect of periodical flows by detecting the arriving rate of green packets early and by demoting or promoting packets randomly at the aggregate flow level [5], [6]. It uses a leaky bucket with a token filling rate equal to the negotiated traffic rate determined by interdomain SLA. The instantaneous token level in the leaky bucket belongs to one of three regions which are demotion, balanced and promotion regions. In the demotion region, before the leaky bucket is emptied, incoming green packets are demoted to yellow packets randomly with a probability which is inversely proportional to the number of remaining tokens that have not be consumed by arriving green packets. In the promotion region, before the leaky bucket is overflowed, incoming yellow packets are promoted to green packets randomly with a probability proportional to the number of remaining tokens.

The early and random marking decision of the REDP marker removes the deterministic phase effect common for UDP sources that brings about unfairness when using the leaky bucket marker [5]. Consequently, the REDP marker demotes green packets of each flow proportionally to its current green transmission rate through the early and random marking decisions on packets. Therefore, in the case of demotion for UDP sources having the same contracted rate, a fair amount of yellow packets could be generated to each UDP flow through the REDP marker because those UDP flows have the same current green transmission rate. And if the aggregate contracted rate of UDP flows is larger than the bottleneck link bandwidth on their path and the negotiated rate is set as the bottleneck link bandwidth, it is sure that the demotion occurs and the aggregate green packets of UDP flows uses completely the bottleneck link where almost all the yellow and red packets would be dropped by the RIO buffer [7]. Then, each UDP flow get a fair throughput composed of almost geen packets. Otherwise if the aggregate contracted rate of UDP flows is larger than the bottleneck link bandwidth and the negotiated rate is set smaller than the bottleneck link bandwidth, each UDP flow get a fair throughput composed of a fair amount of geen and that of yellow packets. This UDP fairness in demotion of the REDP marker results in the UDP fairness in promotion where a fair amount of yellow packets of each UDP flow through the prior demotion are promoted to a fair amount of green packets through the early and random marking decision. The UDP fairness of the REDP marker is almost as good as the per-flow marking while it works at the aggregate flow level without any scalability problem [5]. However, the REDP marker cannot remove the phase effect completely for TCP sources. As a result, TCP fairness of the REDP marker is not obvious as for UDP sources [5].

In the case that TCP sources, having a same contracted rate and different connection round trip times (RTT), share the bottleneck link bandwidth through the RIO buffer, each TCP flow will have an unfair green transmission rate due to the TCP's congestion control worked with a different RTT. And if the REDP marker demotes green packets of those TCP flows with unfair green transmission rates, an unfair amount of yellow packets having a larger drop probability than green packets will be generated to each TCP flow. Even if each TCP flow has the same green transmission rate, TCP fairness is not obvious because the bottleneck link cannot be utilized completely by green packets of those TCP flows due to the TCP's congestion control and then some amount of red packets of TCP flows having different packet transmission rates would not be dropped at the bottleneck link. Consequently, the unfair packet transmission rate due to the TCP's congestion control results in TCP unfairness of the REDP marker in demotion and promotion. Therefore, to improve TCP fairness of the REDP marker, a controller which can make packet transmission rates of TCP flows fair is needed. Then, more fair packet transmission rates of TCP flows than those using only the REDP marker can improve TCP fairness of the REDP marker in demotion and promotion.

In this paper, to improve TCP fairness of the REDP marker, we combine a dropper and an input Yellow meter with the REDP marker. To make packet transmission rates of TCP flows more fair, at the aggregate flow level the combined dropper drops incoming excessive green packets randomly with a constant probability when the token level in the leaky bucket stays in demotion region without incoming yellow packets. The incoming green packet not dropped by the combined dropper will be demoted randomly. Then, incoming some green packets of each TCP flow will be dropped proportionally to its current green transmission rate. Generally, the green packets are generated more constantly and larger than the red packets from each TCP flow. Then, the dropping of green packets is more effective than the dropping of red packets to make packet transmission rates of TCP flows fair. So, the packet transmission rates and green transmission rates of TCP flows can be more fair and TCP fairness can be improved through the combined dropper. The combined dropper performs a dropping in the demotion at a domain boundary only if there is no prior demotion. The concatenate dropping at multiple domains is avoided to manifest the effect of a dropping at a domain boundary on TCP fairness. We have experimented with the REDP marker with the combined dropper on the *ns2* simulator for TCP sources [8]. The simulation results show that the REDP marker with the combined dropper improves TCP fairness in demoting and promoting packets by generating fair yellow traffic compared to the REDP marker. The effectiveness of the selected drop probability is also investigated with showing its impact on the performance of the REDP marker with the combined dropper.

The rest of the paper is organized as follows. Section 2 proposes the combined dropper to improve TCP fairness of the REDP marker in demoting and promoting packets. The REDP marker is also explained in this section. Section 3 studies the performance of the REDP marker with the combined dropper using *ns2* network simulator. Section 3 also shows the effectiveness of the selected drop probability through simulation results. Section 4 is devoted to concluding remarks.

II. REDP Marker with a combined dropper

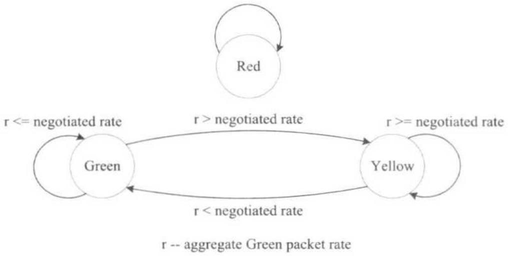


Fig. 1. State diagram of demotion and promotion.

In this Section, we propose the combined dropper to improve TCP fairness of the REDP marker in demoting and promoting packets. The REDP scheme uses a variation of the tricolor marking model for the tricolor promotion. Therefore, each packet can be marked as green, yellow, or red. Suppose an end user submits an expected rate *r*. Initially, the local domain configures a leaf marker for the flow. A packet of this flow is marked as green if it is in-profile and red if it is out-of-profile. None of the packets is marked as yellow. While crossing a domain boundary through the REDP marker, a green packet is demoted to yellow if the aggregate green packet rate exceeds the negotiated rate at the intermediate marker. A yellow packet is promoted to green if the aggregate green packet rate is lower than the negotiated rate. A yellow packet is never demoted to red and a red packet is never promoted to yellow. Thus, yellow is specifically used to memorize the demoted green packets. In promoting packets, the REDP marker provides better assured services than the two-color promotion through the tricolor promotion [5]. Figure 1 shows the state diagram of the demotion-promotion algorithm in the REDP marker.

The REDP marker introduces randomness and early decisions on the packet marking process at the aggregate flow level to remove the phase effect that could bring about the unfairness in the demotion and promotion among different microflows [5], [6]. The REDP marker is implemented using a leaky bucket where the token filling rate *R* is equal to the negotiated rate determined by interdomain SLA. A promotion threshold is set in the leaky bucket. If the tokens in the leaky bucket exceed the promotion threshold and an arriving packet is yellow, it is randomly promoted to green. Similarly, a demotion threshold is used in the leaky bucket. If the number of tokens in the leaky bucket is less than the demotion threshold, an arriving green packet is randomly demoted to yellow. Using this scheme, the REDP marker can also detect whether the aggregate rate of the arrival of green packets is lower or higher than the negotiated rate. The REDP marking model is shown in Fig. 2. Two thresholds, T_L and T_H, divide the leaky bucket into three regions - demotion, balanced, and promotion regions. If the arriving rate of green packets is equal to the token filling rate *R*, the token consumption rate is the same as the token filling rate. Therefore, the number of tokens in the bucket remains in the balanced region and each packet is forwarded without changing the color. If the arriving rate of green packets exceeds *R*, the token consumption rate exceeds the token filling rate. Then, the token level in the bucket falls into the demotion region. In the demotion region, each arriving green packet is randomly demoted to yellow with a probability of P_{demo}, where P_{demo} is a function of the token count in the leaky bucket TK_{num} as shown in Eq.(1). In Eq.(1), MAX_{demo} is the maximum demotion rate. When the leaky bucket runs out of tokens, each arriving green packet is demoted to yellow. If the arriving rate of green packets is less than *R*, the token filling rate exceeds the token consumption rate and the token level reaches the promotion region. In the promotion region, each arriving yellow packet will be randomly promoted to green with a probability of P_{promo}, where P_{promo} is a function of TK_{num} as shown in Eq.(1).

$$P_{demo} = (T_L - TK_{num}) \cdot MAX_{demo} / T_L$$
$$P_{promo} = (TK_{num} - T_H) \cdot MAX_{promo} / (b - T_H) \qquad (1)$$

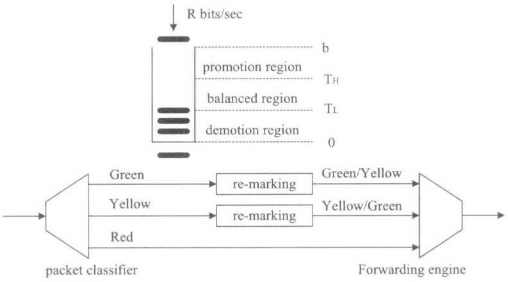


Fig. 2. REDP Marker

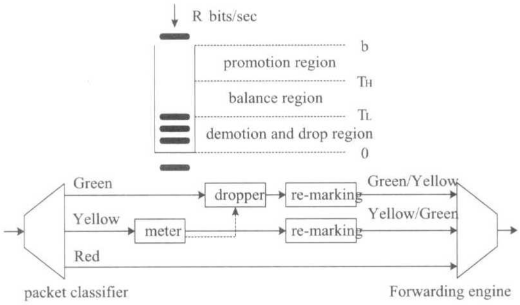


Fig. 3. REDP Marker with a combined dropper

The DiffServ core routers could support either two or three drop precedences. If it supports two drop precedences (e.g., RIO), green is deemed as "in". Both yellow and red are deemed as "out" [7]. In this paper, we consider the case that it supports two drop precedences. As described before, the REDP marker was proposed to remove the phase effect of periodical flows by detecting the arriving rate of green packets early and by promoting or demoting packets randomly. The early and random marking decision of the REDP marker removes the deterministic phase effect common for UDP sources which generate constant data rates. Consequently, the REDP marker demotes green packets of each flow proportionally to its current green transmission rate through the early and random marking decisions on packets. As a result, UDP fairness of the REDP marker in demoting and promoting packets is almost as good as the per-flow marking while it works at the aggregate flow level without any scalability problem. However, the REDP marker cannot remove the phase effect completely for TCP sources and TCP fairness of the REDP marker is not obvious as for UDP sources [5].

The REDP marker with combined a dropper and an input Yellow meter is shown in Fig. 3. To improve TCP fairness of the REDP marker without scalability problem, at the aggregate flow level the dropper drops incoming excessive green packets randomly with a constant probability when the token level in the leaky bucket stays in demotion region without incoming yellow packets. It performs a dropping in the demotion at a domain boundary only if there is no prior demotion. The concatenate dropping at multiple domains is avoided to manifest the effect of a dropping at a domain boundary on TCP fairness. The combined input Yellow meter identifies whether there is a prior demotion or not. The incoming green packet not dropped by the combined dropper will be demoted randomly. Then, incoming some green packets of each TCP flow will be dropped proportionally to its current green transmission rate. Generally, the green packets are generated more constantly and larger than the red packets from each TCP flow. So, the dropping of green packets is more effective than the dropping of red packets to make packet transmission rates of TCP flows fair while the RIO buffer drops red packets randomly more than green packets.

If TCP sources with a same contracted rate and different connection RTTs share the bottleneck link bandwidth through the RIO buffer, each TCP flow will have an unfair green transmission rate through the bottleneck link. And if the REDP marker demotes green packets of those TCP sources with unfair green transmission rates, it will demote green packets of each TCP flow proportionally to each TCP flow's current unfair green transmission rate. To improve TCP fairness in demoting green packets, yellow packets should be generated to each TCP flow proportionally to its current green transmission rate and a portion of those yellow packets of each TCP flow proportional to that rate should be dropped at the RIO buffer. So, the packet transmission rates and green transmission rates of those TCP flows can be more fair. Then, the REDP marker will demote green packets of each TCP flow proportionally to each TCP flow's more fair green transmission rate. But, those yellow packets of each TCP flow are randomly dropped at the RIO buffer with a variable probability which is based on congestion state at the bottleneck link [7]. Then, a yellow packet may or may not get dropped depending on the actual network traffic and those yellow packets of each TCP flow would not be dropped proportionally to its current green transmission rate. But, the combined dropper drops incoming excessive green packets with a constant probability P_{drop} at demotion region. Therefore, incoming some green packets of each TCP flow will be dropped proportionally to its current green transmission rate and the combined dropper can improve TCP fairness in demoting green packets compared to the REDP marker. This improved TCP fairness by the combined dropper in demotion results in improved TCP fairness in promotion. In promotion, where a fair amount of yellow packets of each TCP flow through the prior demotion with the combined dropper are promoted to a fair amount of green packets through the early and random marking decision of the REDP marking scheme. The simulation results in Subsection 3-A of this paper support this argument.

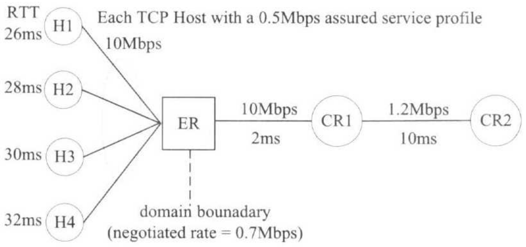
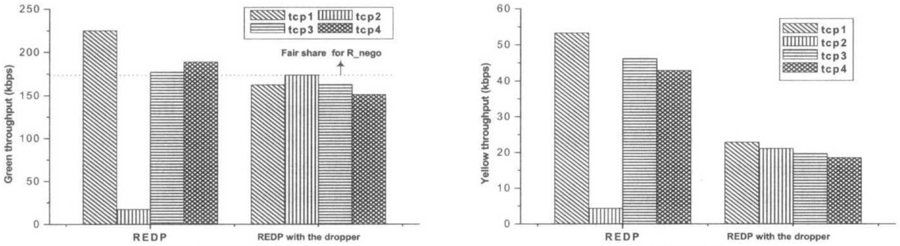


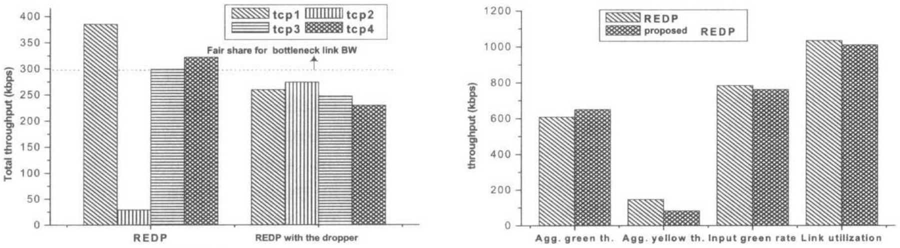
Fig. 4. Simulation topology used to study the effect of the combined dropper on TCP fairness in demotion.

III. Performance Study

In this Section, we analyze the performance of the REDP marker with the combined dropper. In the previous Section, we claimed that the combined dropper improves TCP fairness in the demotion compared to the REDP marker. We consider the demotion and promotion cases to show the effect of the combined dropper on TCP fairness. In each case, we compare TCP fairness and aggregate throughput through experiments using the *ns2* simulator. Only TCP sources are analyzed to show the performance improvement. Finally, we briefly investigate the effectiveness of the selected P_{drop} probability with showing its impact on the performance of the REDP marker



(a) Green throughput (b) Yellow throughput



(c) Total throughput (d) Aggregate throughput

Fig. 5. Comparisons of TCP fairness and aggregate throughput at Fig. 4.

with the combined dropper.

A. Effect of the combined dropper on TCP fairness in demotion and promotion

Figure 4 depicts the simulation topology used to study the effect of the combined dropper on TCP fairness in demotion. TCP hosts at all simulation results used TCP Reno transport protocol and TCP hosts H1, H2, H3, H4 each has a leaf marker implemented inside. Each of the hosts has a 0.5 Mbps assured service profile. So initially each host could have up to 0.5 Mbps packets marked as green. The remaining packets are marked as red. Assured service is implemented in routers through the RIO scheme. In core routers, all the green packets are treated as "in," both red and yellow packets are treated as "out". We implemented a simple RIO queue [7] in *ns2* simulator. Both "in" and "out" packets are buffered in the same queue. We used two sets of RED parameters for "in" and "out" packets [9]. The RED parameters for "in" packets is : 45 packets, 60 packets, and 0.02 for $\min_{in}$, $\max_{in}$, and $P\max_{in}$, respectively, and 20 packets, 40 packets, and 0.05 for $\min_{out}$, $\max_{out}$, and $P\max_{out}$, respectively, where $\min_{in}$ and $\max_{in}$ represent the lower and upper bounds for the average queue size for "in" packets, and $P\max_{in}$ is the maximum drop probability for an "in" packet when the queue size is in the $[min_{in}, max_{in}]$ range. The $\min_{out}$, $\max_{out}$, and $P\max_{out}$ are the corresponding parameters for the "out" packets. So almost all the green packets would be forwarded without being dropped in this configuration. The RTT (Round Trip Time) of each TCP flow is 26, 28, 30, 32 ms, respectively. Four TCP flows-tcp1, tcp2, tcp3, tcp4-originate from hosts H1, H2, H3, and H4, respectively and terminates at CR2. Throughput of each TCP flow is measured at CR2 core router. The edge router ER is located at the domain boundary.

In Fig. 4, at ER, the negotiated rate R is 0.7 Mbps and there is 1.2 Mbps bottleneck link bandwidth between CR1 and CR2. The aggregate contracted rate of those TCP hosts is 2.0 Mbps which is larger than the bottleneck link bandwidth. Therefore, Figure 4 shows the case where ideally the aggregate green packets of TCP flows can utilize all the bottleneck link bandwidth. In this paper, we focused on the improvement of TCP fairness of the REDP intermediate marker. The intermediate marker in edge router is assumed to have no signalling for exchanging information with the leaf marker in each host for the ease of scalability. The REDP marker in ER performs the marking process with 0.7 Mbps token filling rate. For both markers in all our simulations, we set the size of the leaky bucket, b, as 60 packets where T_L is set as 15 packets and T_H is set as 45 packets. Both MAX_{demo} and MAX_{promo} probabilities are set equally as 0.5 [5]. The drop probability P_{drop} in the combined dropper is set constantly as 0.02. In Fig.4, the input yellow traffic rate is zero. Then, the combined dropper performs the random dropping in demotion at ER. In Fig.4, ideally, at edge router ER, 1.2 Mbps green packets for the 1.2 Mbps bottleneck link bandwidth can arrive but only 0.7 Mbps of them could be marked as green. If the marker implemented in ER is ideally fair, as for UDP sources, each TCP flow should have 175 Kbps packets forwarded as green and 125 Kbps packets demoted as yellow [5]. The green packets could pass the bottleneck link. Therefore ideally, each TCP flow should get 175 Kbps green throughput and 300 Kbps total throughput.

The throughput for different TCP flows at Fig.4 using the REDP marker and the REDP marker with the combined dropper is shown in Fig.5. We show green, yellow, and total throughputs of each TCP flow to analyze the effect of combined dropper on TCP fairness in demotion. In addition, aggregate throughput performances of those TCP flows using both markers are also compared. In Fig.5-(d), we can see that the input green rate of aggregate TCP flows at ER is much smaller than the bandwidth of the bottleneck link due to the TCP's congestion control. Because the negotiated rate is smaller than the input green rate in Fig.4, it is certain that the token level can stay in the demotion region and the arriving green packets are randomly dropped at demotion region by the combined dropper.

Figure 5-(a) shows green throughput of each TCP flow. In results using the REDP marker in Fig.5-(a), the green throughput of the four TCP flows is highly biased. The tcp2 flow only gets about 25 Kbps green throughput while other each TCP flow gets a green throughput larger than 175 Kbps. Results as this can also be seen in Figs.5-(b) and 5-(c). This results can be explained as followings. The increase in the packet transmission rate of each TCP flow depends on its RTT. Therefore, a TCP flow which has a smaller RTT can transmit more packets compared to other flows which have a larger RTT. This means that TCP flows with different RTTs have inherent unfairness. Furthermore, the TCP transmission property that the packet transmission rate of TCP exponentially increases or decreases with its RTT makes the congestion state at CR1 vary radically with a period as the phase effect [6]. The radical and periodic variation of congestion state at RIO buffer results in the case that packets of only certain TCP flows are dropped more frequently due to the buffer overflow drop or the random drop according to the average queue length of RIO buffer. Therefore, throughputs of those TCP flows are much smaller than that of other TCP flows and can be almost zero at the worst case. This TCP unfairness occurs because TCP has its own congestion control algorithm and the RIO buffer drops arriving packets according to its congestion state [7], [10]. To improve TCP fairness, a control to make packet transmission rates of TCP flows more fair should be added. Using only the aggregate marking algorithm as the REDP at intermediate marker cannot avoid that TCP unfairness [5].

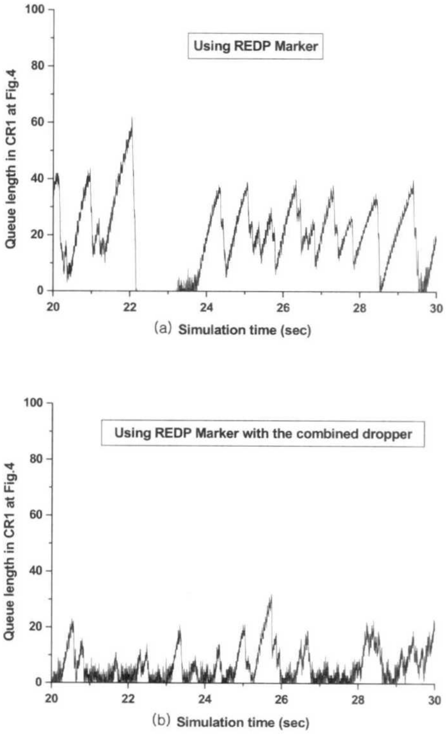


Fig. 6. Comparison of queue length variations in CR1.

On the other hand, in results using the REDP marker with the combined dropper in Fig.5-(a), TCP fairness in green throughput is improved compared to the REDP marker and each TCP flow gets approximately 175 Kbps green

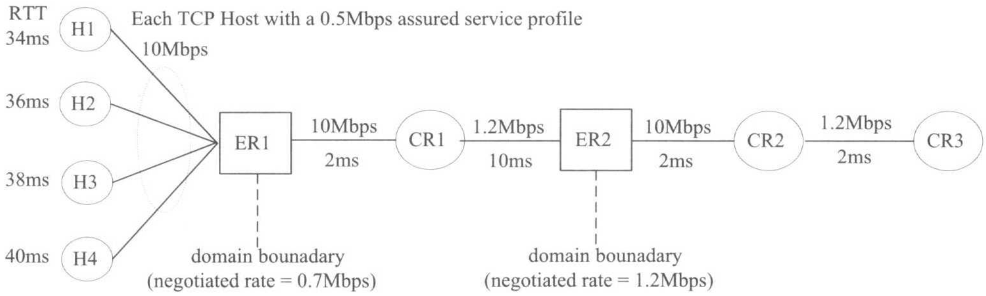


Fig. 7. Simulation topology used to study the effect of combined dropper on TCP fairness in promotion.

throughput. This improved TCP fairness in green throughput results in improved fairness in yellow throughput as shown in Fig.5-(b) because of the demotion fairness of REDP marking process [5]. Furthermore, the improved TCP fairness in yellow throughput results in improved TCP fairness in following promotion. In Fig.5-(c), TCP fairness in total throughput is also improved by using the combined dropper. These results show that as a controller to make packet transmission rates and green transmission rates of TCP flows more fair, the combined dropper improves TCP fairness of the REDP marker in demotion while it works at the aggregate flow level without any scalability problem. In addition, Figure 5-(d) shows that the combined dropper can increase aggregate green throughput and decrease aggregate yellow throughput. This means that using the combined dropper the aggregate contracted packets of TCP flows can be dropped less at the next domain. But, utilization of the bottleneck link and input green rate are not improved compared to the REDP marker. Figure 6 compares variations of queue length of RIO buffer in CR1 at Fig.4. In Fig.6-(a) using the REDP marker, we can see the burst packet arrivals of TCP flows with global synchronizations due to the phase effect [6]. But, when using the REDP marker with the combined dropper, the phase effect of TCP flows that could bring about the unfairness in demotion and promotion among different microflows is reduced as shown in Fig.6-(b).

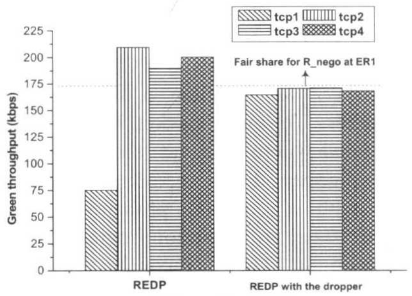
The topology shown in Fig.7 is simulated to study the effect of the combined dropper on TCP fairness in promotion. Each of the hosts has a 0.5 Mbps assured service profile. The RTT of each TCP flow is 34, 36, 38, 40 ms, respectively. Similar to the simulation in Fig.4, H1, H2, H3, H4, each has a flow starting from it and sinking at CR3. Throughput of each TCP flow is measured at CR3. ER1 and ER2 are two edge routers, each of which has an intermediate marker implemented in it. CR1, CR2, and CR3 are core routers with built-in RIO mechanism. Each flow crosses two domain boundaries. At the first domain boundary defined by ER1, the negotiated rate is 0.7 Mbps and the bandwidth of the bottleneck link in the first domain is 1.2 Mbps between CR1 and ER2. At the second domain boundary defined by ER2, the negotiated rate is 1.2 Mbps and the bandwidth of the bottleneck link in the second domain is 1.2 Mbps between CR2 and CR3. At ER1, the input yellow traffic rate was zero and then the combined dropper randomly drops incoming green packets in demotion region. At ER2, the input yellow traffic rate was not zero because of the generation of yellow packets at ER1. So, the combined dropper will not perform the random dropping at ER2. In this paper, the concatenate dropping at multiple domains is avoided to manifest the effect of a dropping at a domain boundary on TCP fairness. Therefore, the marking processes in both markers at ER2 are same.

The throughput for different TCP flows at Fig.7 using both markers is shown in Fig.8. We show green, yellow, and total throughputs of each TCP flow to analyze the effect of the combined dropper on TCP fairness in promotion. Figure 8-(a) shows green throughput of each TCP flow. In Fig.7, the aggregate contracted rate of those TCP hosts is 2.0 Mbps larger than the 1.2 Mbps bottleneck link bandwidth. If the intermediate markers implemented in ER1 and ER2 are ideally fair, as for UDP sources, ideally each TCP flow can get 175 Kbps green throughput and 125 Kbps yellow throughput at ER2 by the marker in ER1. Then, by promotion of the marker in ER2, ideally each TCP flow can get 300 Kbps green throughput at CR3. However, similar to the results in Fig.5, total input green rate of aggregate TCP flows at ER1 is smaller than the 1.2 Mbps bandwidth of the bottleneck link due to the TCP's congestion control. Therefore, though the intermediate markers in Fig.7 are ideally fair, throughput of each TCP flow cannot have the above ideal value because yellow and red packets of each TCP flow are dropped more frequently with a larger probability than green packets in RIO buffer at CR1 and CR2.

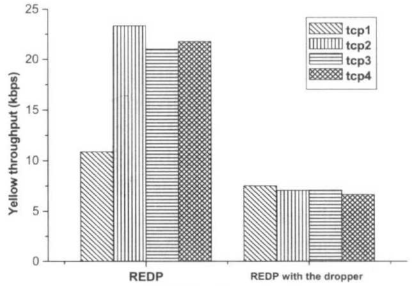
In results using the REDP marker in Figs.8-(a), 8-(b), and 8-(c), the TCP fairness of REDP marker is not obvious as for UDP sources [5]. On the contrary, in results using the REDP marker with the combined dropper in Fig.8-(a), TCP fairness in green throughput is improved and each TCP flow gets approximately 175 Kbps green throughput which is the ideally fair share for the 0.7 Mbps negotiated rate *R* at ER1. In Figs.8-(a), 8-(b), and 8-(c), the REDP marker with the combined dropper also improves TCP fairness in promotion compared to the REDP marker. The improved TCP fairness in demotion as shown in Fig.5 results in this improved TCP fairness in promotion. Firstly, as shown in Fig.5-(b), a more fair amount of yellow packets of each TCP flow than that using the REDP marker is generated through the prior demotion which is performed with the combined dropper. And then, in promotion, the more fair amount of yellow packets of each TCP flow are promoted to a more fair amount of green packets through the early and random marking decision of the REDP marking process.

B. Effectiveness of P_{drop} for REDP marker with the combined dropper on TCP fairness

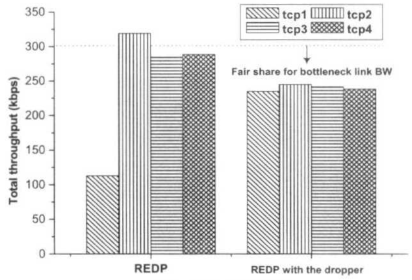
In this Subsection, we briefly investigate the effectiveness of the selected P_{drop} probability for the REDP marker with the combined dropper on TCP fairness through the simulation results. At all the simulations in Subsection 3-A, the P_{drop} probability in the combined dropper is set constantly as 0.02. We show the effectiveness of the selected P_{drop} probability for the REDP marker with the combined dropper by comparing the results using various P_{drop} probabilities such as 0.01, 0.02, 0.03, 0.04, and 0.05 at Fig.4. Firstly, we compare the standard deviation in green throughputs and that in total throughputs of TCP flows for each P_{drop} at Fig.4 as shown in Fig.9-(a). The standard deviation of the throughputs defines the degree of fairness and the standard deviation is abbreviated as STD in this Subsection. In addition, in Fig.9-(b), we compare aggregate green throughput and aggregate total throughput of TCP flows for each P_{drop}. In Fig.9-(a), the STD in green throughputs of TCP flows is smaller than the STD in total throughputs and it also becomes larger proportionally if the STD in total throughputs becomes larger. We can find that the selected P_{drop} , 0.02, belongs to a available value for the performance improvement of the REDP marker with the combined dropper because each STD value in Fig.9-(a) is lower than others and each aggregate throughput in Fig.9-(b) belongs to a higher value when the P_{drop} probability is set as 0.02.



(a) Green throughput



(b) Yellow throughput

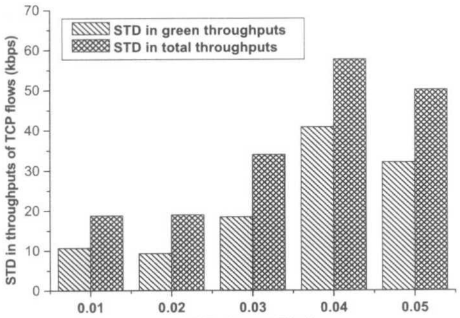


(c) Total throughput

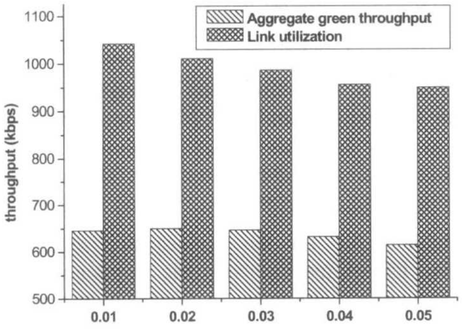
Fig. 8. Comparisons of TCP fairness at Fig. 7.

V. CONCLUDING REMARKS

In this paper, to improve TCP fairness of the REDP marker, we combine a dropper with the REDP marker. To make packet transmission rates of TCP flows more fair, at the aggregate flow level the dropper drops incoming green packets randomly with a constant probability when the token level stays in demotion region without the prior demotion. Then, incoming some green packets of each TCP flow will be dropped proportionally to its current green transmission rate. The combined dropper performs a dropping in the demotion at a domain boundary only if there is no prior demotion. The concatenate dropping at multiple domains is avoided to manifest the effect of a dropping at a domain boundary on TCP fairness. We have simulated the REDP marker with the combined dropper for the demotion and promotion cases to show the effect of the combined dropper on TCP fairness. Simulation results indicate that the REDP marker with the combined dropper improves TCP fairness in demotion and promotion compared to the REDP marker without any scalability problem. The effectiveness of the selected P_{drop} probability is also investigated with showing its impact on the performance of the REDP marker with the combined dropper. From the simulation results, it is inferred that the selected P_{drop} is an available value for the performance improvement of the REDP marker with the combined dropper.



(a) P_drop at Fig.4
(STD : Standard Deviation)



(b) P_drop at Fig.4

Fig. 9. REDP marker with the combined dropper : Effectiveness of P_{drop} for TCP fairness at Fig. 4.

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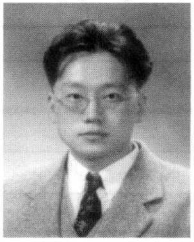

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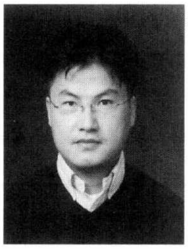

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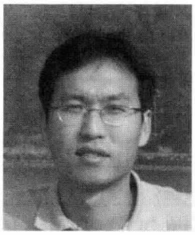

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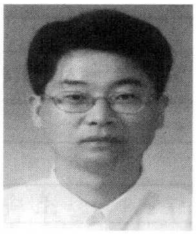

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