A Quantitative Study of Differentiated Services for the Internet

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Abstract—

The Differentiated Services architecture provides router mechanisms for aggregate traffic, and edge mechanisms for individual flows, that together can be used to build services with varying delay and loss behaviors. In this paper, we compare the loss and delay behaviors that can be provided using the services based on combinations of two router mechanisms, *threshold dropping* **and** *priority scheduling* **and two packet marking mechanisms,** *edge-discarding* **and** *edge-marking***. In the first part of our work, we compare the delay and loss behaviors of the two router mechanisms coupled with** *edge-discarding* **for a wide range of traffic arrivals. We observe that** *priority scheduling* **provides lower expected delays to preferred traffic than** *threshold dropping***. In addition, we find that a considerable additional link bandwidth is needed with threshold dropping to provide same delay behavior as priority scheduling. We further observe little difference in the loss incurred by preferred traffic under both router mechanisms, except when sources are extremely bursty, in which case** *threshold dropping* **performs better. In the second part of our work, we examine the throughput of a TCP connection that uses a service built upon** *threshold dropping* **and** *edge-marking***. Our analysis shows that a significant improvement in throughput can be achieved. However, we find that in order to fully achieve the benefit of such a packet marking, the TCP window must take the edge-marking mechanism into consideration.**

I. INTRODUCTION

The diverse and changing nature of service requirements among emerging Internet applications calls for a network architecture that is both flexible and able to distinguish among the needs of the applications. Previous efforts in this direction [26] confirm that a successful deployment of such an architecture necessitates simple mechanisms inside the network. Differentiated Services [1], [4], [20] (diffserv) is such an architecture: the needs of various applications are supported using a simple classification scheme. At a high level, packets are *classified* prior to entering the network via a *packet marking mechanism*, and the services that a router inside the network provides to a packet are solely dependent on the packet's *class*. Several packet marking and router mechanisms have been proposed [4], [5], [10], [12], [14], [16], [24], [25] in the context of this new service paradigm. However there have been few studies providing an understanding of their comparative merits. The intent of our work is to provide a quantitative comparison of these various mechanisms and to derive the loss and delay behavior of the services that these mechanisms support under a wide range of traffic arrivals.

There are two important issues concerning the mechanisms in a diffserv architecture that we examine through our quantitative analysis. The first issue is *how an internal router should treat packets of different classes*. In order to examine this issue, we consider two mechanisms that are representative of two principal proposals [4], [20] that have been widely considered as router mechanisms. In one proposal that is representative of the mechanism in [20], a router maintains separate FIFO queues for each class, and assigns priorities in serving these queues. We refer to this routing mechanism as *priority scheduling*. In the second proposal that is representative of the one in [4], which we refer to as *threshold dropping*, a router allows buffer sharing among packets of all classes. Associated with each class is a threshold that is used to determine whether a packet is accepted or not. Note that while threshold dropping supports multiple service classes by selecting different thresholds, priority scheduling supports multiple service classes by assigning priorities in scheduling the separate buffers. The reason for examining *threshold dropping* and *priority scheduling* mechanisms is that while the latter allows complete isolation among packet classes, the former one does not provide any isolation. As any other router mechanism provides a degree of isolation among packet classes that is between the ranges that provided by the above two router mechanisms, examining *threshold dropping* and *priority scheduling* would provide valuable insights into router mechanisms in the context of diffserv architecture.

The second issue is *whether an edge router should forward packets that fall outside of the "profile"* it has negotiated with the sender [1]. If the edge-router forwards both *in-profile* and *out-profile* packets into the network, the in-profile and out-profile packets of a single session can potentially observe different loss and delay characteristics due to discriminations provided by the internal router mechanisms. The issue of whether out-profile packets should be forwarded into the network or not has been debated in several papers [4], [6], [11], [16]. Some have argued [4],[16] that allowing out-profile packets into the network improves buffer and link bandwidth utilization when routers use threshold dropping. But *the consequence of this approach on the performance of specific network protocols, such as TCP, is not understood*.

The first part of our study compares loss and delay behaviors under the two competing router mechanisms: *threshold drop-*

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[1] Prior to transmission, there is a negotiation between the edge router and the sender regarding a "service class", that specifies a packet classification, and a "service profile", that specifies an upper bound on the amount of traffic that the sender negotiates to send in the specified service class. The edge router marks all the packets that are within the profile as *in-profile* and the excess as *out-profile*.

ping and *priority scheduling* when only in-profile packets are forwarded by an edge-router into the network. In order to gain insight into the fundamental differences in the loss and delay behaviors of these two router mechanisms, we start with Poisson model for packet arrivals. We find that it is possible to provide considerably lower delays to preferred packets with priority scheduling than with threshold dropping. In addition, we find that *an additional* $30\% - 70\%$ *link capacity is needed* with threshold dropping in order to provide the same expected delay to preferred packets as provided by priority scheduling. With respect to loss, we find that both router mechanisms provide similar preferred packet loss rates, with threshold dropping providing marginally lower loss.

Next we examine the validity of the above findings under more realistic packet arrivals that we capture via bursty On-Off sources. Using analytical approach, we observe similar results with the following exception: when the sources are extremely bursty and a very small amount of loss is allowed, threshold dropping utilizes the buffer and link bandwidth more efficiently.

The second part of our study examines the effect that accepting both in-profile and out-profile packets of a session into the network has on a TCP connection with threshold dropping. We assume that in-profile packets are preferred over out-profile packets at internal routers. Based on a simple Markov model, we make two interesting observations for the case when the loss probabilities of the in-profile and out-profile packets are significantly different: 1) there is a significant improvement in the throughput of a TCP connection even when a relatively small portion of traffic is sent as in-profile packets; 2) in order to fully utilize the benefits of such a marking scheme, the choice of the maximum TCP window size should take several parameters into account, such as the loss probabilities of in-profile and out-profile packets, and the sender service profile. Without this, not all of the potential benefits of allowing out-profile packets into the network can be achieved.

Several studies [2], [3], [13], [17], [19], [27] examine delay and/or loss behavior of services in the diffserv architecture using a variety of traffic models. May et al. [17] quantify the expected delay and loss of packets that arrive via a Poisson process, for assured [4] and premium services [20]. Naser et al. [19] quantify the expected delay of packets for constant bit rate and On-Off source traffic using a two-bit architecture which combines assured and premium services. Ibanez et al. [13] consider ways in which assured service can be used to improve TCP throughput, and demonstrate the difficulties in quantifying the impact of assured service on TCP. Yeom et al. [27] perform a similar study, and propose a rather elaborate mechanism to support TCP. Finally, Shenker et al. [2], [3] show that the usefulness of a priority-based service depends heavily on the adaptive capabilities of applications.

While each piece of work contributes to the understanding of the benefits and limitations of the various services, yet the question that, we believe, is of interest to the networking community remains unanswered: given a set of session requirements, what router and packet marking mechanisms should be provided in a diffserv architecture to best satisfy the session requirements? We address this question through a quantitative comparison of the services that are built from two router mechanisms and two packet marking mechanisms. We find that the answer depends on both the service requirements and the traffic model.

The rest of the paper is organized in the following way. In Section 2, we provide the details of diffserv architecture and derive a framework for comparison of two router mechanisms. In Section 3, we compare the router mechanisms when sources are characterized by Poisson arrivals using Markov analysis. In Section 4, we consider traffic that is characterized by Markov modulated On-Off sources and provide comparative analysis via fluid model when the sources require strict quality of service. In Section 5, we study the effect of forwarding both in-profile and out-profile packets of a session on the throughput of TCP connection using the Markov model. Section 6 concludes the paper.

II. Diffserv Architecture and Our Model

The major components of a differentiated services architecture are: (1) edge mechanisms that include metering, marking, shaping and policing individual flows at an edge router and (2) core-router mechanisms,i.e., router mechanisms inside the network for buffering and forwarding aggregate traffic. An edge router provides the access point for the end-host to the core network. Prior to packet transmission, a sender specifies a *service class*, that defines a packet classification, and a *service profile*, that indicates the amount of traffic that the sender negotiates to send in the specified class. The edge router monitors the sending rate to determine if the sender exceeds the service profile. It classifies packets falling within the service profile as *in-profile* and, *out-profile* otherwise, and inserts a tag in the packet header indicating both the service class and whether the packet is in-profile or out-profile. In addition to marking packets, the edge router can decide whether to shape, drop or forward the out-profile packets into the network. As we shall see later, this decision has a significant impact on the network resource utilization, network protocol and service behavior of each class. The router inside the network differentiates the packets based only on their marking by the edge router. As a result, the mechanisms inside the network are simple, requiring no per-flow state information.

In order to compare different router mechanisms that have been previously considered [4], [16], [20], we introduce two router mechanisms, *threshold dropping* (TD) and *priority scheduling* (PS). Most of the router mechanisms that have been considered can be classified as either TD or PS or some variation of these two, based on how they buffer and schedule packets. For the rest of the paper, we assume that router mechanisms distinguish between two classes of packets, *preferred* and *non-preferred*, with packets in the *preferred* class receiving "preference" over the packets in the *non-preferred* class. Let B denote the total buffer size, and B_l^{TD} denote a buffer threshold for non-preferred packets. Let $B(t)$ denote the buffer occupancy at time t. All accepted packets are queued into a single buffer and served according to a *FIFO scheduling mechanism*. A preferred packet arriving at time t is accepted as long as there is space in the buffer, i.e., $B(t) < B$. A non-preferred packet is accepted only if $B(t) \leq B_l^{TD}$. Note that TD allows buffer sharing between preferred and non-preferred packets as long as $B(t) \leq B_l^{TD}$. Under PS router mechanism, the buffer space is partitioned, i.e., one buffer of size B_h^{PS} is allocated to the pre-

Metric	Threshold Dropping
p_h^{TD}	loss probability for preferred packets
p_l^{TD}	loss probability for non-preferred packets
d_h^{TD}	expected delay for preferred packets
d_l^{TD}	expected delay for non-preferred packets
B_l^{TD}	buffer threshold for non-preferred packets
B	total buffer space
Metric	**Priority Scheduling**
p_h^{PS}	loss probability for preferred packets
p_l^{PS}	loss probability for non-preferred packets
d_h^{PS}	expected delay for preferred packets
d_l^{PS}	expected delay for non-preferred packets
B_l^{PS}	buffer allocated to non-preferred packets
B_h^{PS}	buffer allocated to preferred packets

TABLE I

DEFINITION FOR NOTATIONS

ferred packets and the second, of size B_l^{PS}, to the non-preferred packets. A packet is admitted as long as there is space in the corresponding buffer. We assume that the buffers are selected for service according to *strict priority scheduling*, i.e., a non-preferred packet receives service only when the preferred queue is empty.

We consider two packet marking mechanisms, *edge-discard* and *edge-marking*, that an edge router uses to mark the incoming packets of individual flows. The *edge-discard* (ED) mechanism discards the out-profile packets and forwards only in-profile packets into the network. We define the packet marking as *edge-marking* (EM) if both in-profile and out-profile packets are forwarded into the network. We define *a service as a combination of a packet marking and a router mechanism*. In this work we will consider services built by combining ED or EM with TD or PS.

III. THRESHOLD DROPPING VS. PRIORITY SCHEDULING WITH EDGE-DISCARDING: POISSON ARRIVAL MODEL

In this section, we compare the loss and delay characteristics that ED with TD, and ED with PS provide when both preferred and non-preferred packets arrive at an internal router according to Poisson processes. We assume that packet transmission times are exponentially distributed. With an appropriate Markov model formulation, we derive the expressions for loss probability and expected delays that each service offers to preferred and non-preferred packets. We consider *more realistic traffic models* than Poisson arrival in the next section. Our study with Poisson arrivals is meant to first illustrate various issues using simple analysis. We shall be using the notations described in Table I.

A. Markov Model for Threshold Dropping with Edge-discarding

We assume that preferred and non-preferred packets arrive according to Poisson processes with rates λ_h and λ_l respectively. The packet service times are assumed to be exponential random variables with parameter μ. A non-preferred packet is accepted only if the buffer occupancy is less than B_l^{TD} and a preferred packet is accepted as long as there is a space in the buffer. Let $N(t)$ denote the number of packets in the system at time $t \geq 0$, including the one currently being served. It can be easily shown that $\{N(t) : t \geq 0\}$ is a birth-death process. Note that a non-preferred packet is dropped when $N(t) \geq B_l^{TD} + 1$, hence the arrival rate to the buffer when $N(t) \geq B_l^{TD} + 1$ is λ_h and is $\lambda_h + \lambda_l$ when $N(t) < B_l^{TD} + 1$.

Let π_i denote the steady state probability that there are i packets in the system, i.e., $\pi_i = \lim_{t\to\infty} Pr\{N(t) = i\}$. Solving the above birth-death process, we obtain loss probabilities and expected delays for both traffic classes. Let $\rho_h = \lambda_h/\mu$ and $\rho_l = \lambda_l/\mu$. The loss probabilities are given by:

$$p_h^{TD} = \frac{1}{N_f} (\rho_h + \rho_l)^{B_l^{TD}+1} \rho_h^{B-B_l^{TD}} \quad (1)$$

$$p_l^{TD} = \frac{1}{N_f} (\rho_h + \rho_l)^{B_l^{TD}+1} \sum_{i=0}^{B-B_l^{TD}} \rho_h^i \quad (2)$$

where $N_f = \sum_{i=0}^{B_l^{TD}+1} (\rho_h + \rho_l)^i + (\rho_h + \rho_l)^{B_l^{TD}+1} \sum_{i=1}^{B-B_l^{TD}} \rho_h^i$ is the normalization constant. Note that $P_0 = 1/N_f$. Similarly, the expected delay suffered by each traffic type can be derived to be:

$$d_h^{TD} = \frac{P_0}{\mu} \left(1 + \sum_{i=1}^{B_l^{TD}} (i+1) (\rho_h + \rho_l)^i + (\rho_h + \rho_l)^{B_l^{TD}} \sum_{i=1}^{B-B_l^{TD}} (B_l^{TD} + i + 1) \rho_h^i \right) \quad (3)$$

$$d_l^{TD} = \frac{P_0}{\mu} \frac{\left(1 + \sum_{i=1}^{B_l^{TD}} (i+1) (\rho_h + \rho_l)^i\right)}{\sum_{i=1}^{B_l^{TD}} (\rho_h + \rho_l)^i} \quad (4)$$

A closely related analysis with a different packet marking scheme is provided in [17].

B. Markov Model for Priority Scheduling with Edge-discarding

We now derive the corresponding expressions for loss and expected delays when PS is used with TD. We assume the same packet arrival model that we considered with TD. For simplicity, we further assume that buffers are served according to pre-emptive priority scheduling. We expect our results not to differ much from the case when non pre-emptive priority scheduling is used. Let $N(t) = \{N_h(t), N_l(t)\}$ denote the state at time t, where $N_h(t), N_l(t)$ denote the number of preferred and non-preferred packets in the system respectively at time $t \geq 0$. The process $\{N(t) : t \geq 0\}$ is a 2-dimensional Markov chain. Let Q denote the infinitesimal matrix generator for the Markov chain. Let $\pi(i, j)$ be the steady state probability that there are i preferred packets and j non-preferred packets present. Solving $\pi Q = 0$ yields the steady state distribution of the packets in the system. Using this, we find the loss probabilities and expected delays for both classes of traffic. A preferred packet is lost when, upon arrival, it finds B_h^{PS} outstanding preferred packets in the queue. Hence the preferred packet loss probability can be derived as:

$$p_h^{PS} = \sum_{i=0}^{B_l^{PS}+1} \pi(B_h^{PS}+1, i) \quad (5)$$

Similarly, the loss probability for non-preferred packets can be derived as:

$$p_l^{PS} = \sum_{i=1}^{B_h^{PS}+1} \pi(i, B_l^{PS}+1) + \left(1 + \frac{\lambda_h}{\lambda_l}\right) \pi(0, B_l^{PS}+1) \quad (6)$$

The expected delays for each class of traffic can be determined by applying Little's law for each class separately as $d_h^{PS} = \frac{E[N_h]}{\lambda_h(1-p_h^{PS})}$ and $d_l^{PS} = \frac{E[N_l]}{\lambda_l(1-p_l^{PS})}$, where $E[N_h]$, $E[N_l]$ denote the expected number of preferred and non-preferred packets in the system.

C. Comparison of Threshold Dropping and Priority Scheduling

Loss Comparison: We want to compare the preferred packet loss probability as a function of the arrival rate λ_h under TD and PS. In order to make a fair comparison, we choose B_l^{TD}, B_l^{PS}, and B_h^{PS} appropriately so that $p_l^{TD} = p_l^{PS}$. We approach the problem in the following way: First we fix B_l^{TD} and determine the non-preferred packet loss probability p_l^{TD} as a function of arrival rates λ_l and λ_h. We then determine the buffer partition B_l^{PS}, B_h^{PS} such that $p_l^{PS} \le p_l^{TD}$. If multiple partitions satisfy this constraint, we choose the one that minimizes p_h^{PS}. If there is no such partition, we determine the additional amount of buffer that is required to satisfy this condition. Last, we determine p_h^{TD} and p_h^{PS} as a function of arrival rate λ_h of preferred packets for different values of λ_l and B_l^{TD}.

Expected Delay Comparison: Next we compare the expected delay incurred by the preferred packets as a function of arrival rates λ_h and λ_l. Similar to the loss comparison, we first fix B_l^{TD}. For a given value of λ_h and λ_l, we determine p_l^{TD}, p_h^{TD}, and d_h^{TD}. Next we determine the buffer partition B_h^{PS}, B_l^{PS} such that $p_h^{PS} \le p_h^{TD}$ and $p_l^{PS} \le p_l^{TD}$. If multiple partitions satisfy this constraint, we choose the one that minimizes d_h^{PS}. We determine and compare d_h^{TD} and d_h^{PS} as a function of the arrival rate of preferred packets for different values of the non-preferred packet arrival λ_l.

Let us first consider the effect that the choice of B_l^{TD} has on performance. Intuitively, too small a value of B_l^{TD} should result in a very high loss rate for non-preferred packets. On the other hand, too large a value of B_l^{TD} can affect the loss and delay of preferred packets significantly. Hence in order to examine the impact of B_l^{TD}, we consider several values for λ_l and B_l^{TD}. Specifically, we use $\lambda_l = 0.3, 0.5, 0.7$, and $B = 15$, and $B_l^{TD} = 2, 5$. We choose these values for B_l^{TD} following the recommendations in [5] that B_l^{TD} should not be too close to B.

Figure 1(a) compares the expected delays incurred by preferred packets as a function of the preferred packet arrival rate, λ_h, when $B_l^{TD} = 2$. We observe that under PS, preferred packets incur lower expected delays than under TD. As the non-preferred packet arrival rate increases, the expected delay for preferred packets increases under TD. On the other hand, under PS, d_h^{PS} *is not affected by changes in the non-preferred packet arrival rate*. Now we examine the sensitivity of these observations when B_l^{TD} is increased. Figure 1(b) illustrates similar results for $B_l^{TD} = 5$. We observe an increase in the expected delay incurred by preferred packets with threshold dropping over the case when $B_l^{TD} = 2$, while the expected delay is unaffected under priority scheduling. The key observations from these two set of numerical comparisons are:

- Due to buffer isolation and priority scheduling, preferred packets are not affected by the behavior of non-priority packets with the PS router mechanism.
- There is no mechanism to provide lower expected delays to preferred packets with TD without substantially increasing the loss rate of non-preferred packets.

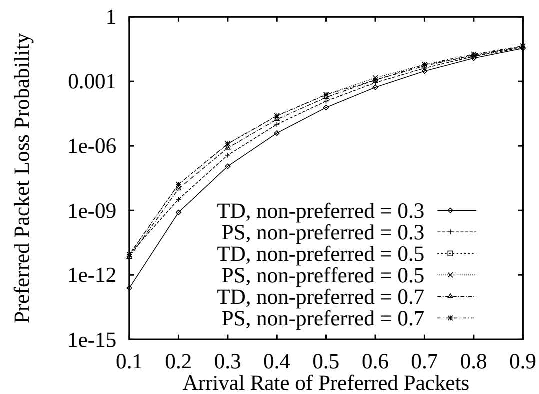


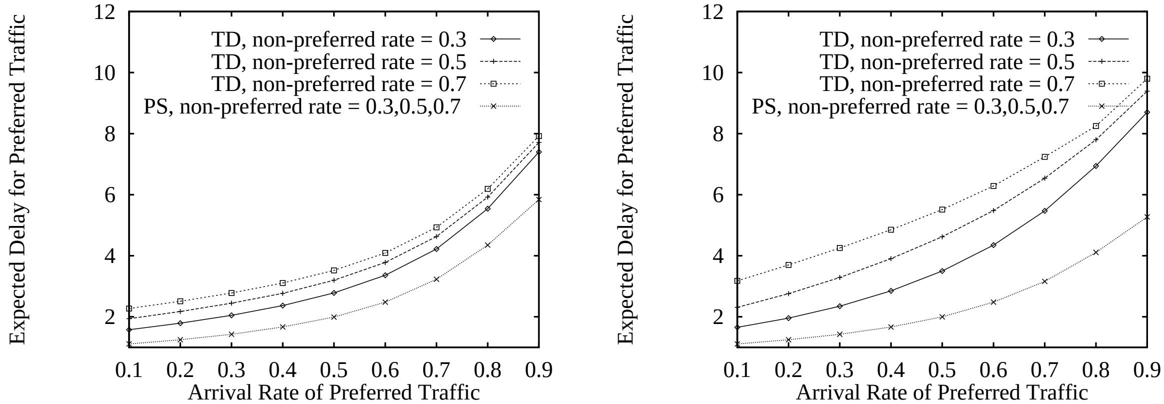
Fig. 2. Loss Comparison with Moderate Provisioning for Non-Preferred Packets

Figure 2 compares the loss probabilities of preferred packets under TD and PS as a function of arrival rates λ_h and λ_l. Here we have chosen $B_l^{TD} = 5$. We observe that for low values of λ_l, preferred packets incur lower loss with TD. However the loss probabilities are similar for higher values of λ_l. This is due to the benefits of buffer sharing under TD, which are more pronounced when λ_l is relatively low. Such sharing is not possible under PS due to buffer partitioning. But under higher arrival rate of non-preferred packets, this multiplexing gain is reduced. With $B_l^{TD} = 2$, we observe even smaller difference between the loss probabilities that preferred packets incur under TD and PS.

D. Excess capacity Analysis and Observations

From the delay and loss comparisons above, we observe that preferred packets incur considerably lower expected delays under priority scheduling. On the other hand, there is very little difference between the preferred packet loss under these two mechanisms, except that, TD provides lower loss to preferred packets when λ_l is smaller. We now ask the question: what additional resources are needed to achieve 1) identical expected delays for preferred packets under threshold dropping, and 2) identical preferred packet loss under priority scheduling.

Let Δc denote the additional link bandwidth that is required under TD to achieve an expected preferred packet delay identical to that under PS. Figure 3 shows the required Δc as a function of the preferred packet arrival rate, λ_h. We observe that $30\% - 70\%$ additional bandwidth is required with TD to achieve



(a) $B_l^{TD} = 2$ (b) $B_l^{TD} = 5$

Fig. 1. Delay Comparison

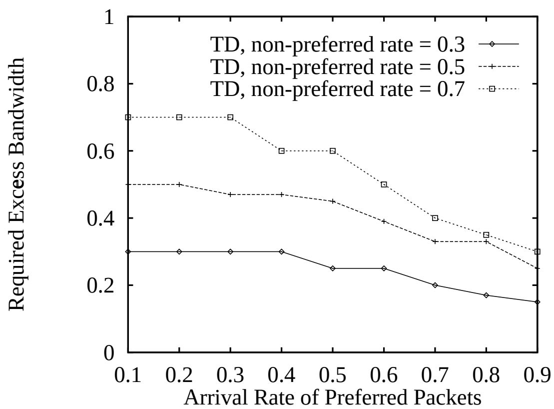


Fig. 3. Excess Bandwidth Required with Threshold Dropping

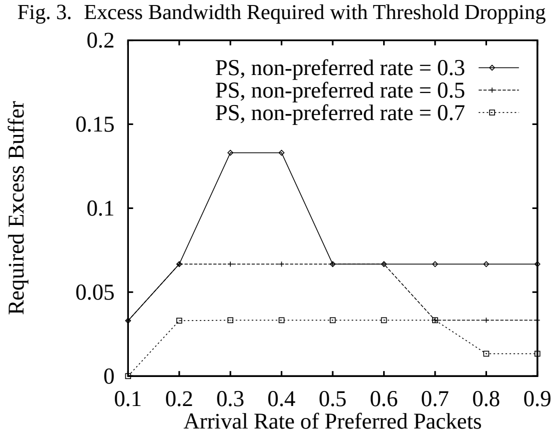


Fig. 4. Excess Buffer Required with Priority Scheduling

identical performance. Figure 4 illustrates the additional amount of buffer that is required in order for PS to achieve the same loss for the preferred traffic as that achieved with TD for the case illustrated in Figure 2. The results indicate that less than 15% additional buffer is sufficient to achieve the same loss rate for preferred packets

Summarizing the results in this section, we observe that preferred packets incur lower delays under PS, and more important, are insensitive to non-preferred packet arrival rate λ_l. We observe that considerable amount of additional bandwidth is needed under TD to provide the same expected delays to preferred packets as with PS. On the other hand, it is possible to achieve a lower preferred packet loss rate under TD, although it is only marginally better than under PS. This is largely due to the benefits of buffer sharing under TD. Moreover, Figure 4 indicate that, with only a small amount of additional buffer, it is possible to achieve identical preferred packet loss under PS.

These two observations lead us to conclude that PS is a better router mechanism in providing loss and delay guarantees, when packets arrive according to a Poisson process. It also suggests that, in order to support multiple levels of services with different delay requirements, PS should be an important component in a diffserv architecture. Our analysis so far has assumed Poisson traffic. In order to understand the effect of bursty arrivals on our findings, we next compare these two mechanisms for bursty arrivals.

IV. Effect of Bursty Sources: Fluid Models

In this section, we examine whether our results change if bursty arrivals are considered. We model bursty arrivals by a set of Markov modulated "On-Off" sources [18]. Each "On-Off" source is characterized by a generator matrix $[G] = \begin{pmatrix} -\alpha & \alpha \\ \beta & -\beta \end{pmatrix}$, where $1/\alpha$ and $1/\beta$ are the mean "Off" and mean "On" periods. The source toggles between the On and Off states, where the duration of the On (Off) period is exponentially distributed with parameter β (α). When a source is in the On state, it transmits fluid at a constant rate r_c and is silent when in the Off state. We define the burstiness, λ, of a source to be the ratio of its mean On and Off periods, i.e., $\lambda = \alpha/\beta$. Source i is then considered to be more bursty than source j if $\lambda_i < \lambda_j$.

We model a constant server with capacity c, that can serve c amount of fluid per unit time. We assume that the preferred traffic is characterized by a homogeneous mix of N On-Off sources. The number of sources that are in the On state at any given time t is described by a Markov chain with generator matrix $[M]$, where $[M]$ can determined from the generator matrix $[G]$. The

$(i,j)^{th}$ element of the matrix $[M]$ is given by:

$$[M]_{ij} = \begin{cases} i\beta & : \quad j = i-1 \\ -(i\beta + (N-i)\alpha) & : \quad j = i \\ (N-i)\alpha & : \quad j = i+1 \end{cases}$$

The non-preferred traffic is modeled by a constant bit rate (CBR) source that transmits fluid at rate r. We further assume that the preferred traffic is inelastic, i.e., the preferred traffic needs strict delay and loss guarantees.

We consider the following scenario for comparing the delay and loss behaviors of TD and PS. In the case of PS, we assume that the peak rate admission control is used to decide whether a preferred source can be admitted or not. This is a specific implementation of premium service [20] that provides no loss and zero delay to preferred traffic. On the other hand, we slightly relax this strict loss and delay requirements with TD, i.e., we allow a loss in the range of 0.001% and a delay of 0.01. The reason for allowing this relaxation is that buffer sharing under TD between preferred and non-preferred traffic makes it impossible to provide zero loss and zero delay to preferred traffic without significantly underutilizing the buffer and link bandwidth. Our intent is to examine (1) whether peak-rate admission control underutilizes the resources with PS when traffic is bursty and (2) whether a slight relaxation in loss and delay requirements makes TD an attractive alternative.

A. Fluid Model for Threshold Dropping with Edge-discarding

Let us first derive the expressions for the loss probability and expected delay for the preferred traffic and loss probability for the non-preferred traffic. We use a similar analysis as in [8]; the main difference between our model and the one in [8] is that, we have uncorrelated preferred and non-preferred traffic. Let Σ_t denote the number of On-Off sources that are in the "On" state at time t . Let Q_t denote the queue length at time t. We denote the set of all possible aggregate On-Off source states by $\mathcal{S} = \{0, 1, 2, \ldots, N\}$. Define $\pi_i(x)$ as the state distribution of the system in equilibrium, when $\Sigma_t = i$ and $Q_t \le x$. Thus $\pi_i(x)$ is denoted by:

$$\pi_i(x) = \lim_{t\to\infty} Pr[\Sigma_t = i, Q_t \le x], \qquad \forall i \in \mathcal{S}, 0 \le x \le B \tag{7}$$

Let $\pi(x)$ denote the vector representing the stationary distribution of the system for queue length less than x, i.e., $\pi(x) = [\pi_0(x), \pi_1(x), \ldots, \pi_N(x)]$. Using the approach as in [18], [8] for modeling fluid sources, the two sets of differential equations can be derived for representing the dynamics of the system. One set of equations describe the behavior when $\Sigma_t < B_l^{TD}$ and the other when $B_l^{TD} < \Sigma_t < B$. These are given by:

$$\frac{d}{dx}\pi(x)[D^{(0)}] = \pi(x)[M], \quad 0 < x < B_l^{TD} \tag{8}$$

$$\frac{d}{dx}\pi(x)[D^{(1)}] = \pi(x)[M], \quad B_l^{TD} < x < B \tag{9}$$

where $[D^{(0)}] = diag\{r-c, r+r_c-c, \ldots, r+Nr_c-c\}$, and $[D^{(1)}] = diag\{-c, r_c-c, 2r_c-c, \ldots, Nr_c-c\}$ are referred as drift matrices. $[D^{(0)}]_{ii}$ represents the rate of change of buffer when i sources are in the "On" state for the case $0 < x < B_l^{TD}$. The solutions of these equations are given by [18]:

$$\pi(x) = \begin{cases} \pi^{(0)}(x) = \sum_{i=0}^{N} a_i^{(0)}\phi_i^{(0)} exp(z_i^{(0)}x) & :0 \le x \le B_l^{TD} \\ \pi^{(1)}(x) = \sum_{i=0}^{N} a_i^{(1)}\phi_i^{(1)} exp(z_i^{(1)}x) & :B_l^{TD} < x \le B \end{cases}$$

where, $\{z_i^{(j)}, \phi_i^{(j)}\}$ are the left eigenvalues and the eigenvectors of $M \cdot D^{(j)^{-1}}$, $j = 0, 1$. Using the techniques in [18] for deriving the closed form solutions for the eigenvalues and eigenvectors, we determine $\{z_i^{(j)}, \phi_i^{(j)}\}$. In order to determine the $2(N+1)$ co-efficients a_i^j, $i = 0, 1, \ldots, N$, $j = 1, 2$, we use the following boundary conditions:

$$\pi_i^{(0)}(0) = 0, \quad i \in \mathcal{S}_U^{(0)} \tag{10}$$

$$\pi_i^{(0)}(B_l^{TD}) = \pi_i^{(1)}(B_l^{TD}), \quad i \in \mathcal{S}_D^{(0)} \cup \mathcal{S}_U^{(1)} \tag{11}$$

$$\pi_i^{(1)}(B) = p_i, \quad i \in \mathcal{S}_D^{(1)} \tag{12}$$

where $p_i = \binom{N}{i}\frac{\alpha^i\beta^{N-i}}{(\alpha+\beta)^N}$, $\quad 0 \le i \le N$ and the set $\mathcal{S}_U^{(j)}$ constitutes the set of all states in $\mathcal{S}$ for which the diagonal elements in the drift matrix $D^{(j)}$ are positive. Similarly $\mathcal{S}_D^{(j)}$ denotes the set of states for which the diagonal elements of the drift matrix are negative. We solve these numerically to determine a_i^j for $0 \le i \le N, j = 1, 2$. Next using the steady state distribution $\pi_i^j(x), j = 1, 2$, we determine $p_h^{TD}, p_l^{TD}, d_h^{TD}$ which are given by:

$$p_h^{TD} = \frac{\sum_{i=0}^{N}\{r + ir_c - c\}\{p_i - \pi_i^{(1)}(B)\}}{\sum_{i=0}^{N} ir_c p_i} \tag{13}$$

$$p_l^{TD} = \sum_{i=0}^{N}\{p_i - \pi_i^1(B_l^{TD})\} + \frac{\sum_{i\in\mathcal{S}_U^0\cap\mathcal{S}_D^1}\{\pi_i^{(1)}(B_l^{TD}) - \pi_i^{(0)}(B_l^{TD})\}\{i + r - c\}}{r} \tag{14}$$

$$d_h^{TD} = \frac{1}{T^{(1)}}\left(\int_{t=0}^{\frac{B_l^{TD}}{c}}\sum_{i=0}^{N} i\pi_i^0(ct)dt + \int_{t=B_l^{TD}}^{B}\sum_{i=0}^{N} i\pi_i^{(1)}(ct)dt + \sum_{i=0}^{N} iP(\Sigma = i, Q = B_l^{TD}) + c\left[1 - \sum_{i=0}^{N}\pi_i^{(1)}(B)\right]\right) \tag{15}$$

where $T^{(1)} = \sum_{i=0}^{N} i\pi_i^{(1)}(B) + c\left[1 - \sum_{i=0}^{N}\pi_i^{(1)}(B)\right]$.

B. Fluid Analysis for Priority Scheduling with Edge-discarding

We next consider the fluid model for ED coupled with the PS router mechanism. We consider a service model that provides zero loss and zero delay guarantees to preferred packets with PS. In order to provide these guarantees, a peak-rate based admission control is required for the admission of sources transmitting preferred traffic [2].

[2]This is a specific implementation of the one defined as expedited forwarding in [14]

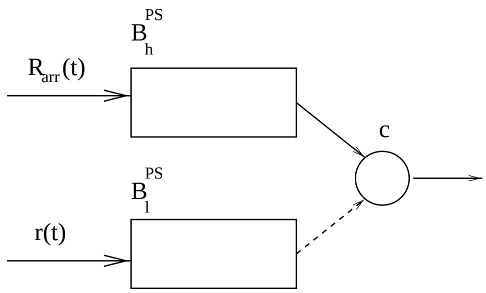


Fig. 5. Fluid Model for Priority Scheduling

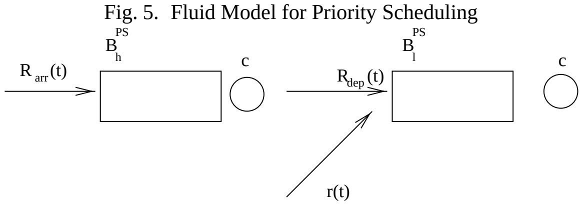


Fig. 6. Equivalent Fluid Model for Priority Scheduling

Figure 5 illustrates the model that we need to analyze for deriving the p_l^{PS}, where $R_{arr}(t)$ denotes the aggregate preferred traffic at time $t > 0$. A key result in [8] states that each traffic class can be analyzed separately as follows: Consider the model shown in Figure 6 where the preferred traffic arrives into the first buffer. The departure process, $R_{dep}(t)$, from the first buffer and the non-preferred traffic arrival at time $t > 0$ together is the arrival process for the second buffer. The loss and delay for preferred traffic can be derived by considering an arrival process $R_{arr}(t)$ into a buffer of size B_h^{PS} and a server of capacity c in isolation. Similarly, the loss for non-preferred traffic can be derived by considering an arrival process $R_{dep}(t) + r(t)$ into a buffer of size B_l^{PS} and a server of capacity c separately.

In our case, $R_{arr}(t) < c$ because of the peak-rate admission control for the preferred traffic; hence $R_{dep}(t) = R_{arr}(t)$. As a result, the loss probabilities of non-preferred traffic can be computed by analyzing a fluid model with an arrival rate $r(t) + R_{arr}(t)$ that is fed into a buffer of size B_l^{PS} and a server with capacity c, where $r(t)$ is the arrival rate of non-preferred traffic in the original model. Thus the analysis for non-preferred traffic reduces to an analysis of a fluid model with a single class traffic [18]. We take $B_l^{PS} = B$ because there is no buffering requirement with preferred traffic due to peak rate admission control.

C. Comparison of Results

Using the analytical models in Section 4.1 and 4.2, we compare the services that use TD and PS for bursty arrivals. As we shall see,

- ED coupled with PS is able to provide better delay behavior to preferred traffic.
- We observe that both TD and PS provide almost identical loss behavior to preferred traffic with one exception. When a source is *extremely bursty*, ED coupled with TD is a better router mechanism.

To simplify the choices in parameters, we use the following normalization: We chose the mean ON period as one time unit, during which one unit of information is generated. The mean

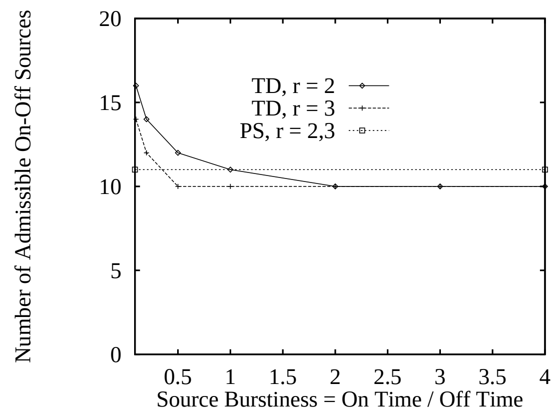


Fig. 7. Loss Comparison as a function of Burstiness

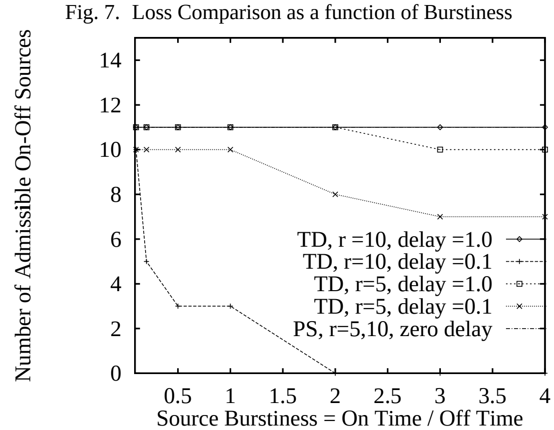


Fig. 8. Delay Comparison as a function of Burstiness

Off period is $1/\lambda$, where $\lambda = \beta/\alpha$. Recall that λ represents the burstiness of a source, i.e., a smaller value of λ means the source is more bursty. For the numerical computations, we vary λ from 0.1 to 4.0. This varies the time spent in the On period from 10% to 75%.

Loss Comparison: The maximum number of preferred sources that can be supported with PS is N_p, where $N_p \leq c \leq N_p + 1$. The admitted preferred traffic with PS experiences no loss because of the peak-rate based admission control. With TD, we determine the number of preferred sources that can be supported such that non-preferred traffic incurs same loss under both the mechanisms and $p_h^{TD} < \tilde{p}_h$, where $\tilde{p}_h$ is the relaxation in loss for preferred traffic.

Delay Comparison: The preferred traffic generated by these N_p sources experience zero delay with PS as there is no buffering for this class of traffic irrespective of non-preferred traffic. Next we determine the number of preferred sources that can be supported with TD for a given arrival rate of non-preferred traffic such that $d_h^{TD} < \tilde{d}_h$, and $p_h^{TD} < \tilde{p}_h$, where $\tilde{d}_h$ and $\tilde{p}_h$ denote the relaxations in delay and loss that we allow with TD for preferred traffic.

Figure 7 compares the number of preferred sources that can be supported with TD and PS as a function of source burstiness, λ, when a very *small amount of loss* for preferred traffic is allowed with TD. We have chosen a server capacity, $c = 11.1$, and total buffer size of 15 data units. The number of preferred sources that can be supported with PS is 11 and this is not affected by the source burstiness. The number of preferred sources that can be supported with TD is heavily influenced by the burstiness of preferred sources. First, we consider a non-preferred arrival rate $r = 2.0$. We observe that, by allowing a preferred traffic loss probability of 10^{-6}, 50% more preferred sources can be supported with TD than with PS when the sources are extremely bursty, i.e., $\lambda = 0.1$. But as the source burstiness decreases (i.e., λ increases), this difference decreases. For $\lambda > 1.0$, PS can support a greater number of sources than TD does when $r = 2.0$. To examine if these results differ when the non-preferred traffic is changed, we consider an arrival rate $r = 3.0$. We observe that PS can support a greater number of preferred sources for $\lambda > 0.4$. This indicates that PS can support a greater number of preferred sources except in the presence of extremely bursty sources. We observe similar results when we allow a loss of 10^{-4} for preferred traffic with TD.

Figure 8 compares the number of preferred sources that can be supported with TD and PS as a function of source burstiness when a *small delay* for the preferred traffic, i.e., $\tilde{d}_h = 0.1, 1.0$, is allowed with TD. Note that PS can support 11 preferred sources providing zero delay irrespective of the non-preferred arrival rate. However we observe that the number of sources that can be supported with TD depends on: (1) the relaxation in delay, $\tilde{d}_h$ that is allowed for the preferred traffic and, (2) the non-preferred arrival rate. When the non-preferred arrival rate, r, is 5.0, and $\tilde{d}_h = 1.0$, TD can support almost same number of sources as PS. But as the non-preferred arrival rate increases to 10, the number of sources that can be supported with TD decreases, although the reduction is not very dramatic. But if the delay relaxation, $\tilde{d}_h$, is reduced to 0.1, there is a sharp decrease in the number of sources that TD can support. For example, when $r = 10.0$ and $\tilde{d}_h = 0.1$, TD cannot support even a single source for $\lambda > 2.0$. *This result illustrates the superiority of PS for preferred sources with stringent delay requirements*.

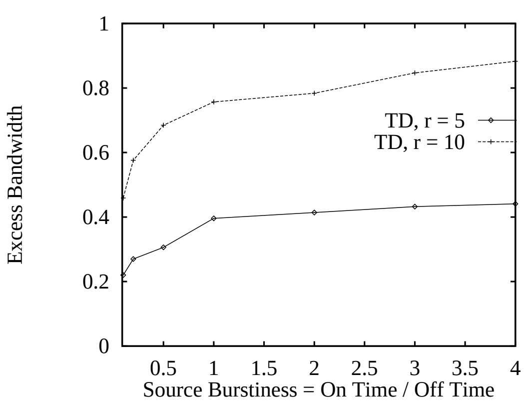


Fig. 9. Excess Bandwidth for TD

Next we evaluate the excess bandwidth Δc that is necessary for TD to be able to support an identical number of sources as PS while providing almost zero delay ($d_h^{TD} < 10^{-3}$) to the preferred traffic. Figure 9 shows the excess bandwidth that is required with TD as a function of λ. We examined both $r = 5.0$ and $r = 10.0$ for the illustration. We find that Δc is as high as 85% for $r = 10$.

Summarizing the results for the bursty sources needing strict loss and delay guarantees, we observe that PS is a better router mechanism for providing lower delays to preferred traffic. We observe that as much as additional 85% bandwidth is necessary with TD to be able to provide similar delays as PS. Comparing the loss behavior, we observe that when the sources are extremely bursty, it is possible to support a larger number of sources with TD if a small amount of preferred traffic loss is tolerated with TD.

V. EDGE-MARKING WITH THRESHOLD DROPPING: TCP SOURCE

We now turn our attention to examining the effect that the EM mechanism coupled with the TD has on the throughput of a TCP connection. Note that EM packet marking can potentially lead to intra-session service differentiation, i.e., in-profile and out-profile packets of a session can incur different loss and delay behaviors. First we derive a Markov model for determining the throughput of a source using TCP Reno taking into account different loss rates. We then examine the effect of forwarding out-profile packets using this Markov model.

A. Stochastic Model for TCP Throughput with Two Loss Regimes

We describe a stochastic model for determining the throughput of a TCP Reno connection when packets use the network service derived from a combination of edge marking (EM), and threshold dropping (TD). We assume an infinite source model for TCP, i.e., the sender has enough data to keep the transmission active. We model the TCP connection in the following way. Let p_1 and p_2 denote the loss rates for in-profile and out-profile packets respectively. Let W_{max} denote the maximum TCP window size. We assume that a packet is marked in-profile if it is within the first W_a packets of the current window, and out-profile otherwise. We also assume that once a packet is lost, all subsequent packets in the same window are also lost. We refer to W_a as the assured window size, i.e., if the window size, $W(t)$ at time $t > 0$, is less than W_a, then all the packets are marked in-profile, and if $W(t) > W_a$, then the first W_a packets are marked in-profile, and the next $W(t) - W_a$ packets are marked out-profile.

We are interested in determining the throughput of this TCP connection as a function of W_a, W_{max}, p_1 and p_2. A recent work [22] models the behavior of TCP Reno as a Markov process for a single service, where all the packets incur the same loss rate. This model has been shown to be reasonably accurate when compared to the measurements over the Internet [21] and with simulation [15]. We modify the above Markov model to account for the two regimes of packet loss that we have assumed for in-profile and out-profile packets. Each state Q_i in the Markov chain represents the current window size W_i, the number of packets that are lost in the previous round L_i, and whether or not the current state is as a result of a timeout T_i. It can be shown easily that $Q_i(t)$ for $t > 0$ is a Markov process. The details of the calculation of the transition probability matrix P, the number of packets that are transmitted by the source when it is in state i and the duration of this state for computing the throughput can be found in [23]. Solving $\pi P = \pi$, we derive the throughput as a function of $p_1, p_2, W_a, W_{max}, RTT$ and the timeout period (TO).

We have described our model as if the service profile is specified as an assured window size W_a. If the service profile is specified as a maximum assured rate [5], R_a, then the following approximation can be used to map R_a into W_a, $W_a \approx RTT * R_a$. Thus, for a given assured rate R_a, the first W_a packets in the current window are marked as in-profile, and if the current window size $> W_a$, the rest of the packets in that window are marked out-profile.

B. TCP Throughput Results for Two Loss Regimes

Using the Markov model in Section 6.1, we examine the effect of edge-marking with threshold dropping on TCP throughput. We compute the throughput seen by a TCP connection as a function of assured window size, W_a, for a fixed maximum window size W_{max}; W_a varies between 0 and W_{max}. When $W_a = 0$, we refer to this as *non-assured TCP* which means that all packets are marked out-profile. When $W_a = W_{max}$, all of the packets of the TCP connection are sent as in-profile packets.

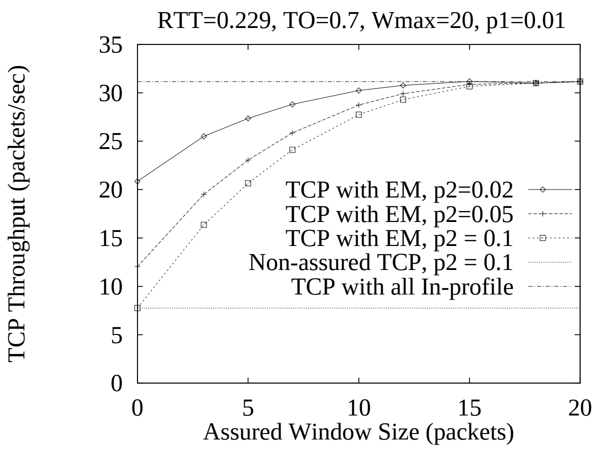


Fig. 10. Throughput of TCP vs. Assured Window Size

Figure 10 shows the throughput (in packets/sec) as a function of the assured window size, W_a (in packets). The loss rates are $p_1 = 0.01$, $p_2 = 0.02, 0.05, 0.1$, W_{max} is 20, $RTT = 0.229$ and $TO = 0.7$. [3] Consider the case when $p_1 = 0.01$ and $p_2 = 0.1$. For the case that $W_a = 0$, i.e., all packets are marked out-profile, the TCP throughput is 8 packets/sec. When $W_a = 20$, i.e., when all packets are marked in-profile, the achievable throughput is 31 packets/sec. We observe that the throughput is an increasing concave function of assured window size, W_a. In addition, we observe a non-linear relationship between throughput and W_a, i.e., most of the benefits are obtained for $W_a = 10$. Thus, the source benefits from using a small assured window size. For example, when $W_a = 5$, it is possible to increase the throughput by 200% over the non-assured TCP throughput. We observe similar trends when we choose different values for out-profile packet loss probability. Comparing the case when $p_2 = 0.1$ with $p_2 = 0.05$, we observe that when p_2 is closer to p_1, the relative improvement in throughput decreases.

[3] We have investigated the above computation of throughput with several other measured values of RTT and TO. We find that the qualitative conclusions of the results do not change.

The above results show the benefits of using in-profile marking when compared to the use of non-assured TCP where all packets are sent as out-profile. We now study the behavior of TCP throughput when W_a is fixed and W_{max} is varied. Figure 11(a) shows the TCP throughput versus W_{max} for a fixed value of W_a. We choose $W_a = 12$, $p_1 = 0.001$, and the same values for RTT and TO used earlier. We observe that throughput increases as W_{max} increases as long as $W_{max} \leq W_a$, irrespective of the value of p_2. This is because when $W_{max} \in (0, W_a)$, all packets are sent as in-profile packets. However the throughput behaves very differently as a function of W_{max} when $W_{max} > W_a$, and is very sensitive to the loss probability of out-profile packets, p_2. For $p_2 = 0.01$, we observe an increase in throughput for $W_{max} > W_a$. However, when $p_2 = 0.05, 0.1$, or 0.2 we observe that TCP throughput decreases for $W_{max} > W_a$. Furthermore, we observe that this decrease in throughput increases with p_2. When we fix $p_1 = 0.01$, we see a smaller decrease in throughput for $W_{max} > W_a$ compared to that observed in Figure 11(a). Figure 11(b) illustrates the results for $W_a = 5$, a smaller assured window than the one used in Figure 11. An interesting observation here is that, except for $p_2 = 0.2$, the throughput increases even after $W_{max} > W_a$ for the range of values we have chosen.

The two key results that we have from the above study for TCP are the following:

- As shown in Figure 10, the throughput of a TCP source is significantly improved over the throughput of the non-assured TCP source when the TCP source chooses to send even a small portion of its packets as in-profile. Also we observe that there is a non-linear relationship between W_a and the observed throughput. The incremental gain in increasing W_a decreases rapidly once reaching a certain threshold. This threshold is dependent on p_1, p_2, and W_{max}. A sender might want to evaluate this threshold for W_a and specify a service profile accordingly.
- Figure 11(a) and Figure 11(b) indicate that the TCP window must take into consideration the service profile, and the loss characteristics for in-profile and out-profile packets. It suggests that once W_a is chosen, W_{max} should be chosen carefully so that the amount of out-profile packets does not exceed the range beyond which it hurts the throughput.

While the first result indicates that there are *added benefits* in using TD with edge-marking, the second result requires the sender to *judiciously choose the fraction of packets* that should be sent as out-profile.

VI. CONCLUSIONS

In this study, we quantitatively examined two key issues for a diffserv architecture: (1) how an internal router should treat packets of different classes, and (2) whether an edge-router should forward packets that fall outside of the service profile. In doing so, we derived analytical models to compare the loss and delay behavior that can be provided using services derived from the combination of two router mechanisms, *threshold dropping* and *priority scheduling* and two packet marking mechanisms, *edge-dropping* and *edge-marking*.

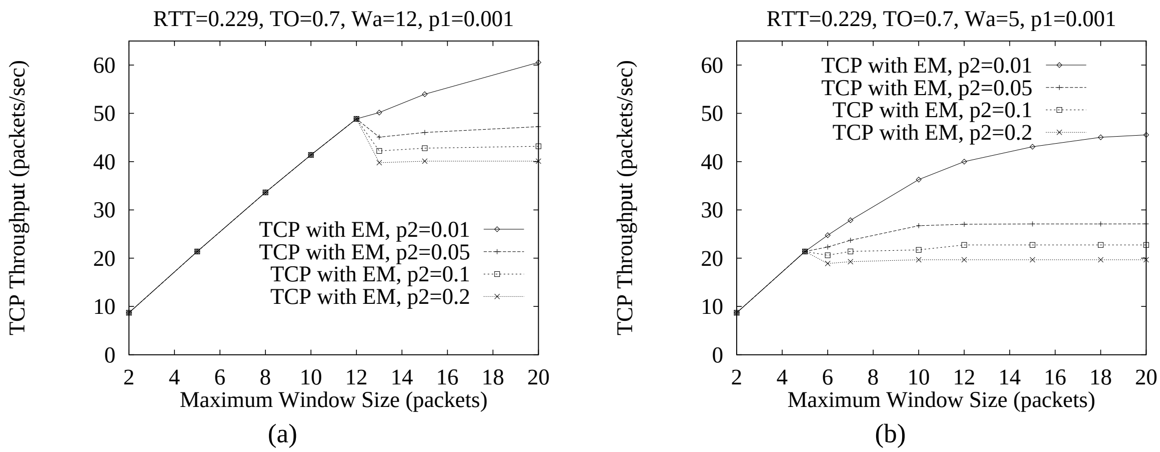


Fig. 11. Throughput of TCP vs. Assured Window Size

The first part of our study compared the loss and delay behavior of service classes derived by combining threshold dropping and priority scheduling with edge-discarding. Our examination of these services under a wide range of traffic models showed that priority scheduling provides lower expected delays to preferred packets. In addition, we found that a considerable additional link bandwidth is needed with threshold dropping to provide the same delay behavior as priority scheduling. We found that both router mechanisms provide similar loss rates to preferred packets with an exception for extremely bursty sources, in which case threshold dropping had better performance. These findings suggest that *priority scheduling should be an important mechanism* in a diffserv architecture for supporting delay sensitive applications.

The second part of our study examined the effect of forwarding out-profile packets into the network on the throughput of a TCP connection. We derived a simple Markov model for determining throughput of a TCP connection when in-profile packets observe different loss rates than out-profile packets. We found that it is possible to improve the throughput significantly even when a small portion of traffic is sent as in-profile packets. However, we observed that in order to fully utilize the benefit of out-profile packets, a TCP source must carefully determine the amount of out-profile packets it will send in addition to the in-profile packets. This result suggests that it is *beneficial to combine edge-marking with threshold dropping for throughput sensitive applications*. However, intra-session service differentiation can adversely affect the performance of a feedback-based network protocol if proper attention is not given to the choice of out-profile packets that a source should send.

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