Size-based Scheduling to Improve Web Performance

Mor Harchol-Balter* Bianca Schroeder Nikhil Bansal Mukesh Agrawal

School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213
$\langle$harchol,bianca,nikhil,mukesh$\rangle$@cs.cmu.edu

Abstract

Is it possible to reduce the expected response time of *every* request at a web server, simply by changing the order in which we schedule the requests? That is the question we ask in this paper.

This paper proposes a method for improving the performance of web servers servicing static HTTP requests. The idea is to give preference to those requests which are short, or have small remaining processing requirements, in accordance with the SRPT (Shortest Remaining Processing Time) scheduling policy.

The implementation is at the kernel level and involves controlling the order in which socket buffers are drained into the network.

Experiments are executed both in a LAN and a WAN environment. We use the Linux operating system and the Apache and Flash web servers.

Results indicate that SRPT-based scheduling of connections yields significant reductions in delay at the web server. These result in a substantial reduction in mean response time, mean slowdown, and variance in response time for both the LAN and WAN environments.

Significantly, and counter to intuition, the *large requests* are only negligibly penalized or not at all penalized as a result of SRPT-based scheduling.

1 Introduction

A client accessing a busy web server can expect a long wait. This paper considers how we might reduce this wait for the case of *static* requests, of the form "Get me a file." Measurements [29, 27, 18] have suggested that the request stream at most web servers is dominated by *static* requests. Serving static requests *quickly* is the focus of many companies *e.g.*, Akamai Technologies, and much ongoing research.

In this paper we will be concerned with *response time* which is defined to be the time from when the client sends out the SYN-packet requesting to open a connection until the client receives the last byte of the file requested.

Our idea is simple. Traditionally, requests at a web server are time-shared: the web server proportions its resources fairly among those requests ready to receive service. We call this scheduling policy **FAIR** scheduling. We propose, instead, *unfair scheduling*, in which priority is given to short requests, or those requests with short remaining time, in accordance with the well-known scheduling algorithm preemptive Shortest-Remaining-Processing-Time-first (**SRPT**). It is well-known from queueing theory that SRPT scheduling minimizes queueing time, [37]. Allowing short jobs to preempt long jobs is desirable because forcing long jobs to wait behind short jobs results in much lower mean response time than the situation where short jobs must wait behind long jobs. Our expectation is that using SRPT scheduling of requests at the server will reduce the queueing time at the server, and therefore the total response time.

Despite the obvious advantages of SRPT scheduling with respect to mean response time, applications have shied away from using this policy for two reasons: First SRPT requires knowing the *size of the request*[1] (i.e. the time required to service the request). Our experiments show that the size of a request is well-approximated by the file size, which is well-known to the server. We found a linear relationship between the service time of the request, modulo a small overhead. Second, there is the fear that SRPT "starves" big requests [9], [39] (p. 410), [38] (p. 162). A primary goal of this paper will be to investigate whether this fear is valid in the case of

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[1] Strictly speaking, it is not the size of the request but the size of the response that we are talking about. We use these two terms interchangeably.

web servers serving typical web workloads.

It is not immediately clear what SRPT means in the context of a web server. A web server is not a single-resource system. To understand *which* of the web server's resources need to be scheduled, we need to understand which resource in a web server experiences high load first, i.e., which is the *bottleneck* resource. The three contenders are: the CPU; the disk to memory bandwidth; and the server's limited fraction of its ISP's bandwidth. On a site consisting primarily of *static content*, a common performance bottleneck is the limited bandwidth which the server has bought from its ISP [25, 12, 4]. Even a fairly modest server can completely saturate a T3 connection or 100Mbps Fast Ethernet connection. Also, buying more bandwidth from the ISP is typically relatively more costly than upgrading other system components like memory or CPU. In fact, most web sites buy sufficient memory so that all their files fit within memory (keeping disk utilization low) [4]. For static workloads, CPU load is typically not an issue.

In this paper, we model the limited bandwidth that the server has purchased from its ISP by placing a limitation on the server's uplink, as shown in Figure 1. In all our experiments (using both a 10Mbps and 100 Mbps uplink, and 256 MB of RAM, and running various trace-based workloads) the bandwidth on the server's uplink is always the bottleneck resource. **System load** is therefore defined in terms of the load on server's uplink. For example, if the web server has a 100 Mbps uplink and the average amount of data requested by the clients is 80 Mbps, then the system load is 0.8. Although in this paper we assume that the bottleneck resource is the limited bandwidth that the server has purchased from its ISP, the main ideas can also be adapted for alternative bottleneck resources.

The focus in the rest of the paper will be on how to schedule the server's uplink bandwidth, and the performance effects of this scheduling. To schedule the server's uplink bandwidth, we need to apply the SRPT algorithm at the level of the network. Our approach is to control the order in which the server's socket buffers are drained. Recall that for each (non-persistent) request a connection is established between the client and the web server. Corresponding to each connection, there is a socket buffer on the web server end into which the web server writes the contents of the requested file. Traditionally, the different socket buffers are drained in Round-Robin Order, with equal turns being given to each connection with data ready to send. Thus each ready connection receives a fair share of the bandwidth of the server's uplink. We instead propose to give priority to those sockets corresponding to connections for small file requests or where the *remaining data* required by the request is small. Throughout, we use the Linux OS.

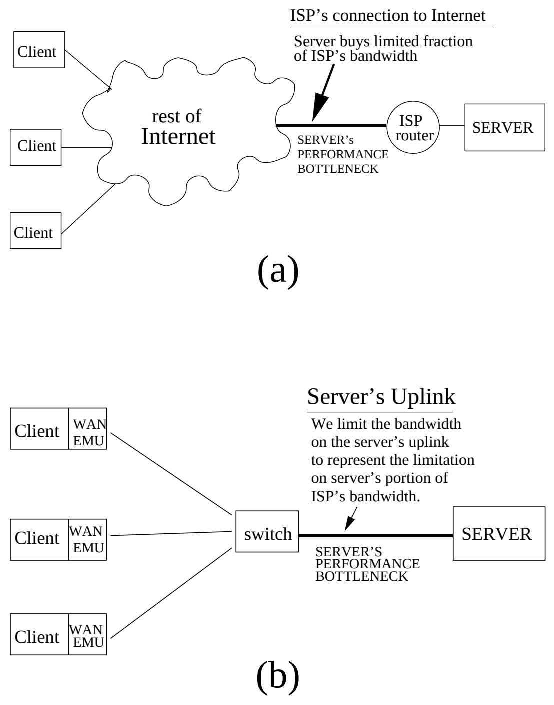

ISP's connection to Internet
Server buys limited fraction of ISP's bandwidth
Client
Client
Client
rest of Internet
SERVER'S PERFORMANCE BOTTLENECK
ISP router
SERVER
(a)
Server's Uplink
We limit the bandwidth on the server's uplink to represent the limitation on server's portion of ISP's bandwidth.
Client
WAN EMU
Client
WAN EMU
Client
WAN EMU
switch
SERVER
SERVER'S PERFORMANCE BOTTLENECK
(b)

Figure 1: *(a) Server's bottleneck is the limited fraction of bandwidth that it has purchased from its ISP. (b) How our implementation setup models this bottleneck by limiting the server's uplink bandwidth.*

The goal of this paper is to compare FAIR scheduling with SRPT scheduling. These are defined as follows:

FAIR scheduling This uses standard Linux (fair-share draining of socket buffers) with an unmodified web server.

SRPT scheduling This uses modified Linux (SRPT-based draining of socket buffers) with the web server modified only to update socket priorities.

We experiment with two different web servers: the common Apache server [19], and the Flash web server [33], which is known for speed. Since results are quite similar, we primarily show here only the results for the case of Apache, and leave the Flash results for the associated technical report [24]. Our clients make requests according to a web trace, which specifies both the time the request is made and the size of the file requested. Experiments are also repeated using requests generated by a web workload generator.

Experiments are executed first in a LAN, so as to isolate the reduction in queueing time at the server. Response time in a LAN is dominated by queueing delay at the server and TCP effects. Experiments are next repeated in a WAN environment. The WAN allows us to incorporate the effects of propagation delay, network loss, and congestion in understanding more fully the client experience. WAN experiments are executed both using a WAN emulator and by using geographically-dispersed client machines.

Synopsis of results obtained for a LAN:

- SRPT-based scheduling decreases mean response time in a LAN by a factor of 3 – 8 for system load greater than 0.5 (recall that system load is the utilization of the server's uplink.)
- SRPT-based scheduling helps small requests a lot, while negligibly penalizing large requests. Under a system load of 0.8, 80% of the requests improve by a factor of 10 under SRPT-based scheduling. Only the largest request suffers an increase in mean response time under SRPT-based scheduling (by a factor of only 1.2).
- The variance in the response time is far lower under SRPT as compared with FAIR, in fact two orders of magnitude lower for most requests.
- There is no negative effect on network throughput or CPU utilization from using SRPT as compared with FAIR.

Synopsis of results obtained for a WAN:

- Propagation delay significantly diminishes the improvement of SRPT over FAIR. Nevertheless, for an RTT of 100ms, under a system load of 0.9, SRPT's improvement over FAIR is still a factor of 2.
- Network loss diminishes the improvement of SRPT over FAIR further. Under high network loss (10%), SRPT's improvement over FAIR is only 25% under a system load of 0.9.
- Unfairness to large jobs remains negligible under WAN conditions, as under LAN conditions.

Section 2 describes our implementation of SRPT scheduling. Section 3 describes the LAN experimental setup and the LAN results. Section 4 describes the WAN experimental setup and the WAN results. Section 5 provides an in depth look at *why* SRPT scheduling improves over FAIR scheduling. Section 6 describes previous work. Finally in Section 7, we elaborate on broader applications of SRPT-based scheduling, including its application to other resources, and to non-static requests. We also discuss SRPT applied to web server farms and Internet routers.

2 Implementation of SRPT

In Section 2.1 we explain how socket draining works in standard Linux, and we describe how to achieve priority queueing in Linux (versions 2.2 and above). Section 2.2 describes the implementation end at the web server and also deals with the algorithmic issues such as how to choose good *priority classes* and the setting and updating of priorities. Furthermore we consider the problem that for small requests, a large portion of the time to service the request is spent *before* the size of the request is even known, and we find a solution for this problem.

2.1 Achieving priority queueing in Linux

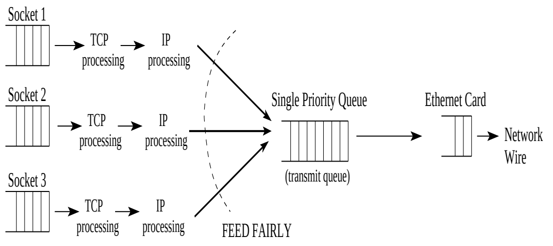
Figure 2(left) shows data flow in standard Linux.

There is a socket buffer corresponding to each connection. Data streaming into each socket buffer is encapsulated into packets which obtain TCP headers and IP headers. Throughout this processing, the packet streams corresponding to each connection is kept separate. Finally, there is a *single*[2] "priority queue" (*transmit queue*), into which *all* streams feed. All streams that have data ready to send take *equal* turns draining into the priority queue. Although the Linux kernel does not explicitly enforce fairness, we find that under conditions where clients are otherwise equal, TCP governs the flows so that they share fairly on short time scales. This single "priority queue," can get as long as 100 packets. Packets leaving this queue drain into a short Ethernet card queue and out to the network.

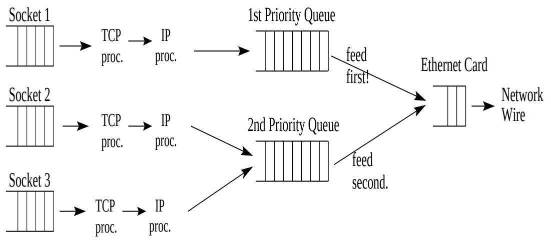
To implement SRPT we need more priority levels. To do this, we first build the Linux kernel with support for the user/kernel Netlink Socket, QOS and Fair Queueing, and the Prio Pseudoscheduler. Then we use the `tc`[2] user space tool to switch the Ethernet card queue from the default 3-band queue to the 16-band prio queue. Further information about the support for differentiated services and various queueing policies in Linux can be found in [21, 34, 2, 3].

Figure 2(right) shows the flow of data in Linux after the above modification: The processing is the same until the packets reach the priority queue. Instead of a single priority queue (transmit queue), there are 16 priority queues. These are called bands and they range in number from 0 to 15, where band 15 has lowest priority and band 0 has highest priority. All the connections of priority i feed fairly into the ith priority queue. The priority queues then feed in a prioritized fashion into the Ethernet Card queue. Priority queue i is only allowed

[2]The queue actually consists of 3 priority queues, a.k.a. bands. By default, however, all packets are queued to the same band.



(a) Standard Linux - FAIR



(b) Modified Linux - SRPT

Figure 2: *(Left) Data flow in standard Linux. The important thing to observe is that there is a* single *priority queue into which all ready connections drain fairly. (Right) Linux with priority queueing. It is important to observe that there are several priority queues, and queue i is serviced only if all of queues 0 through $i-1$ are empty.*

to flow if priority queues 0 through $i-1$ are all empty.

A note on experimenting with the above implementation of priority queueing: Consider an experiment where each connection is assigned to one of two priorities. We have found that when the number of simultaneous connections is very low, the bandwidth is not actually split such that the first priority connections get 100% of the bandwidth and the second priority connections get 0% of the bandwidth. The reason is that with very few connections, the first priority connections are unable to fully utilize the link, and thus the second priority connections get a turn to run. However, when the number of simultaneous connections is higher (e.g., above 10), this is not a problem, and the first priority connections get 100% of the bandwidth. In all the experiments in this paper, we have hundreds of simultaneous connections and the above implementation of priority queueing works perfectly.

2.2 Modifications to web server and algorithmic issues in approximating SRPT

The modified Linux kernel provides mechanisms for prioritized queueing. In our implementation, the Apache web server uses these mechanisms to implement the SRPT-based scheduling policy. Specifically, after determining the size of a request, Apache sets the priority of the corresponding socket by calling `setsockopt`. As Apache sends the file, the remaining size of the request decreases. When the remaining size falls below the threshold for the current priority class, Apache updates the socket priority with another call to `setsockopt`.

2.2.1 Implementation Design Choices

Our implementation places the responsibility for prioritizing connections on the web server code. There are two potential problems with this approach. These are the overhead of the system calls to modify priorities, and the need to modify server code.

The issue of system call overhead is mitigated by the limited number of `setsockopt` calls which must be made. Typically only one call is made per connection. Even in the worst case, we make only as many `setsockopt` calls as there are priority classes (6 in our experiments) per connection.

A clean way to handle the changing of priorities totally within the kernel would be to enhance the `sendfile` system call to set priorities based on the remaining file size. We do not pursue this approach here as neither our version of Apache (1.3.14) nor Flash uses `sendfile`.

2.2.2 Size cutoffs

SRPT assumes infinite precision in ranking the remaining processing requirements of requests. In practice, we are limited to only 16 priority bands (16).

Based on experimentation, we have come up with some *rules-of-thumb* for partitioning the requests into priority classes which apply to the heavy-tailed web workloads. The reader not familiar with heavy-tailed workloads will benefit by first reading Section 5.

Denoting the cutoffs by $x_1 < x_2 < \ldots < x_n$:

- The lowest size cutoff x_1 should be such that about 50% of requests have size smaller than x_1. The requests comprise so little total load in a heavy-tailed distribution that there's no point in separating them.

- The highest cutoff x_n needs to be low enough that the largest (approx.) .5% – 1% of the requests have size $> x_n$. This is necessary to prevent the largest requests from starving.

- The middle cutoffs are far less important. Anything remotely close to a logarithmic spacing works well.

In the experiments throughout this paper, we use only 6 priority classes to approximate SRPT. Using more improved performance only slightly.

2.2.3 Priority to SYNACKs

At this point one subtle problem remains: For small requests, a large portion of time to service the request is spent during the connection setup phase, *before* the size of the request is even known. The packets sent during the connection startup might therefore end up waiting in long queues, making connection startup very costly. For short requests, a long startup time is especially detrimental to response time. It is therefore important that the SYNACK be isolated from other traffic. Linux sends SYNACKs, to priority band 0. It is important when assigning priority bands to requests that we:

1. Never assign any sockets to priority band 0.

2. Make all priority band assignments to bands of *lower* priority than band 0, so that SYNACKs always have highest priority.

Observe that giving highest priority to the SYNACKs doesn't negatively impact the performance of requests since the SYNACKs themselves make up only a negligible fraction of the total system load.

Giving priority to SYNACKs is important in SRPT because without it the benefit that SRPT gives to small requests is not noticeable. Later in the paper (Section 5.1) we consider whether the FAIR policy might also benefit by giving priority to SYNACKs, but find the improvement to FAIR to be less significant.

2.2.4 The final algorithm

Our SRPT-like algorithm is thus as follows:

1. When a request arrives, it is given a socket with priority 0 (highest priority). This allows SYNACKs to travel quickly as explained in Section 2.2.3.

2. After the request size is determined (by looking at the URL of the file requested), the priority of the socket corresponding to the request is reset based on the size of the request, as shown in the table below.

Priority	Size (Kbytes)
0 (highest)	-
1	$\leq$ 1K
2	1K - 2K
3	2K - 5K
4	5K-20K
5	20K - 50K
6 (lowest)	$>$ 50K

3. As the remaining size of the request diminishes, the priority of the socket is dynamically updated to reflect the remaining size of the request.

3 LAN setup and results

In Section 3.1 we describe the experimental setup and workload for the LAN experiments. Section 3.2 compares SRPT versus FAIR with respect to mean response time, in a LAN environment. Section 3.3 again compares SRPT versus FAIR in a LAN environment, but this time with respect to their performance on large requests. Finally Section 3.4 illustrates a simplification of the SRPT idea which involves only two priorities and yet still yields quite good performance.

3.1 LAN experimental setup

3.1.1 Machine Configuration

Our experimental setup involves six machines connected by a 10/100 Ethernet switch. Each machine has an Intel Pentium III 700 MHz processor and 256 MB RAM, and runs Linux 2.2.16. One of the machines is designated as the server and runs Apache 1.3.14. The other five machines act as web clients and generate requests as described below. Below we show results for both the case where the server uplink bandwidth is 10 Mbps and the case where the server uplink bandwidth is 100 Mbps. For the case of the 10 Mbps bandwidth, at any moment in time there may be a couple hundred simultaneous connections at the server. For the case of 100 Mbps bandwidth the number of simultaneous connections is in the thousands.

In all the figures throughout, unless stated otherwise, we assume that the server's uplink bandwidth is 10 Mbps.

3.1.2 Open versus closed systems

To properly evaluate the performance of a server it is important to understand how clients generate requests which drive the web server. The process by which clients generate requests is typically modeled either as an *open system* or as a *closed system*, as shown in Figure 3.

In an *open system* each user is assumed to visit the web site just once. The user requests a file from the web site, waits to receive the file, and then leaves. The point is that a request completion *does not* trigger a new request. A new request is only triggered by a new user arrival.

In a *closed system* model, it is assumed that there is some fixed number of users, say N users. These sit at the same web site forever. Each user repeats these 2 steps, indefinitely: (i) request a file, (ii) receive the file. In a closed system, a new request is only generated at the time of completion of a previous request — request completions trigger new requests.

When using a trace to generate requests under an open system model, the requests are generated at the times indicated by the trace, where interarrival times have been scaled to create the appropriate test system load. When using a trace to generate requests under a closed system model, the arrival times of requests in the trace are ignored. New requests are only triggered by completions of requests.

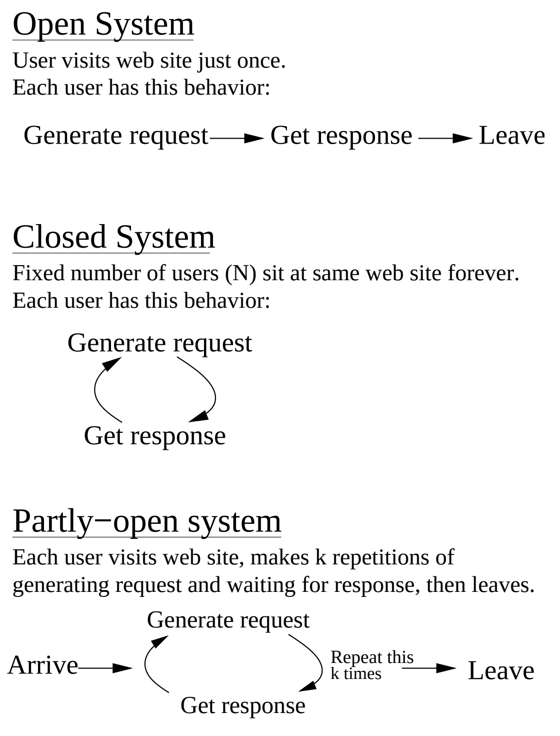

Open System
User visits web site just once.
Each user has this behavior:
Generate request
Get response
Leave
Closed System
Fixed number of users (N) sit at same web site forever.
Each user has this behavior:
Generate request
Get response
Partly−open system
Each user visits web site, makes k repetitions of
generating request and waiting for response, then leaves.
Generate request
Arrive
Repeat this
k times
Leave
Get response

Figure 3: *Three models for how the requests to a web server are generated. In all cases, every individual request set out averages into the mean response time. We present results for an open system and for a partly-open system, where we look at a range of k.*

Neither the open system model nor the closed system model is entirely realistic. Throughout this paper we use the open system model. We also present results, however, for a different model which we call the *partly-open model*. The partly-open model is more realistic because it captures properties of both the open and closed models. Under the partly-open model, each user is assumed to visit a web site, make k requests for files at the web site, and then leave the web site. The k requests are made consecutively, with each request completion triggering the next request. In Section 3.2 we will show the performance of our web server assuming both an open system model and a partly-open system model, as a function of k. We will find that the results are largely similar to an open model.

In all the figures below, unless otherwise stated, we assume an open system model.

3.1.3 Trace-based workload

Throughout the paper we use a trace-based workload consisting of 1-day from the Soccer World Cup 1998, obtained from the Internet Traffic Archive [22]. The trace contains 4.5 million HTTP requests, virtually all of which are *static*. In our experiments, we use the trace to specify *the time* the client makes the request and the *size in bytes* of the request.

The entire 1 day trace contains requests for approximately 5000 different files. Given the mean file size of 5K, it is clear why all files fit within main memory. This explains why the disk is not a bottleneck. Each experiment was run using a busy hour of the trace (10:00 a.m. to 11:00 a.m.). This hour consisted of about 1 million requests.

Some additional statistics about our trace workload: The minimum size file requested is a 41 byte file. The maximum size file requested is about 2 MB. The distribution of the file sizes requested fits a heavy-tailed truncated Pareto distribution (with α-parameter ≈ 1.2). The largest $< 3\%$ of the requests make up $> 50\%$ of the total system load, exhibiting a strong heavy-tailed property. 50% of files have size less than 1K bytes. 90% of files have size less than 9.3K bytes. The distribution of file sizes is shown in Figure 4.

We also repeated all experiments using a *web workload generator*, `Surge` [8] to generate the requests at the client machines. The `Surge` workload is created to be statistically representative of the file sizes at a web site, the sizes of files requested from a web site, the popularity of files requested, and more. We modified `Surge` simply to make it an open system. We have included in the associated technical report [24] the same set of results for the `Surge` workload. The `Surge` workload had a higher mean request size (7K, rather

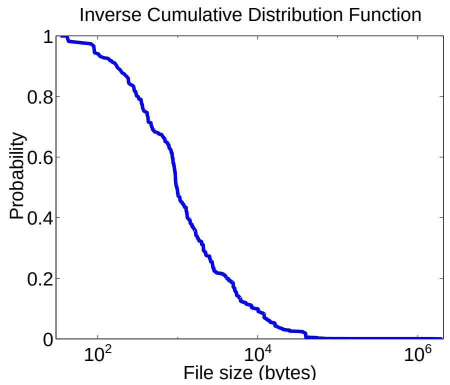


Figure 4: *Inverse Cumulative Distribution Function, $\overline{F}(x)$, for the trace-based workload.* $\overline{F}(x) = \Pr\{$*Job size* $> x\}$

than 5K), however in all other respects was statistically very similar to our trace-based workload. Not surprisingly, the factor improvement of SRPT over FAIR is very similar under the `Surge` and trace-based workloads. To be precise, all the response times for both FAIR and for SRPT are 50% higher under the `Surge` workload, and therefore the factor improvement is the same.

3.1.4 Generating requests at client machines

In our experiments, we use `sclient` [5] for creating connections at the client machines. The original version of `sclient` makes requests for a certain file in periodic intervals. We modify `sclient` to read in traces and make the requests according to the arrival times and file names given in the trace.

To create a particular system load, say 0.8, we simply scale the interarrival times in the trace's request sequence until the average number of bits requested per second is 8Mb/sec. We validate the system load both analytically and via measurement.

3.1.5 Performance Metrics

For each experiment, we evaluate the following performance metrics:

- *Mean response time.* The response time of a request is the time from when the client submits the request until the client receives the last byte of the request.

- *Mean slowdown.* The slowdown metric attempts to capture the idea that clients are willing to tolerate long response times for large file requests and yet expect short response times for short requests. The slowdown of a request is therefore its response time divided by the time it would require if it were the sole request in the system. Slowdown is also commonly known as *normalized response time* and has been widely used [9, 36, 16, 23].

- *Mean response time as a function of request size.* This will indicate whether big requests are being treated *unfairly* under SRPT as compared with FAIR-share scheduling.

3.2 Mean improvements of SRPT under LAN

Before presenting the results of our experiments, we make some important comments.

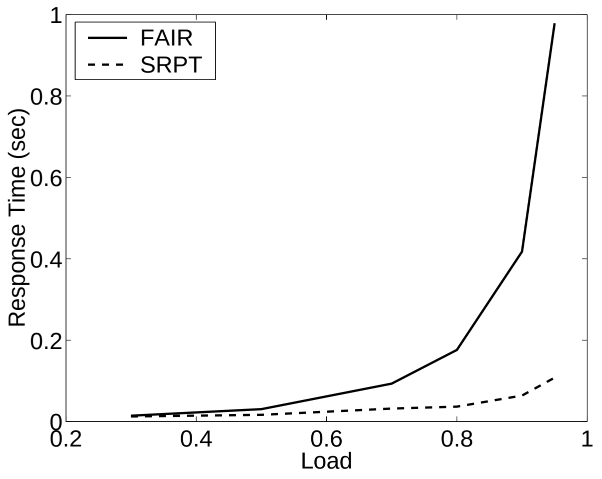
- In all of our experiments the server's uplink bandwidth was the bottleneck resource. CPU utilization during our experiments remained below 5% for all the 10 Mbps experiments and below 80% for the 100 Mbps experiments, even for system load 0.95.

- The measured throughput and bandwidth utilization under the experiments with SRPT scheduling is *identical* to that under the same experiments with FAIR scheduling. The same exact set of requests complete under SRPT scheduling and under FAIR scheduling.

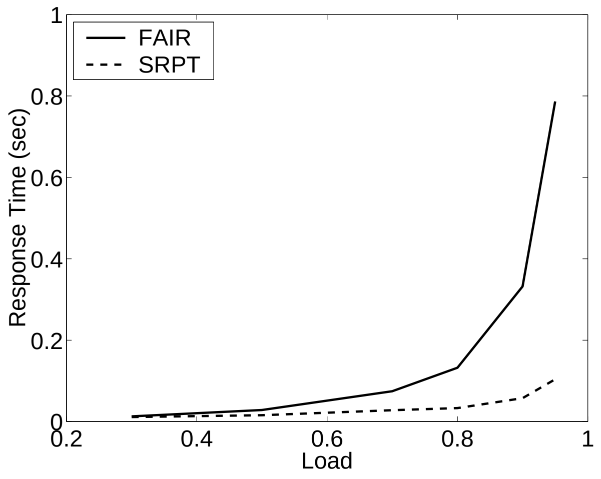
- There is no additional CPU overhead involved in SRPT scheduling as compared with FAIR scheduling. Recall that the overhead due to updating priorities of sockets is insignificant, given the small number of priority classes that we use.

Figure 5 shows the mean response time under SRPT scheduling as compared with the traditional FAIR scheduling as a function of system load. Figure 5(a) assumes that requests are generated according to an open model and Figure 5(b) assumes a partly-open system model, where each user generates $k = 5$ requests. Results are very similar in (a) and (b). For lower system loads the mean response times are similar under FAIR and SRPT. However for system loads > 0.5, the mean response time is a factor of 3 – 8 lower under SRPT scheduling.

Another way to state the results in Figure 5 is to observe that the mean response time under FAIR with a system load of 0.5 is the same as the mean response time under SRPT with a system load of 0.85. Thus SRPT can be viewed as offering an increase in throughput of 3.5 Mbps under a 10 Mbps uplink, without a sacrifice in response time.



(a) Open system model



(b) Partly-open system model

Figure 5: *Mean response time under SRPT versus FAIR as a function of system load, under trace-based workload, in LAN environment uplink bandwidth 10 Mbps. (a) Assumes open system model (b) Assumes partly-open system model with $k = 5$ request-iteration cycles per user.*

The performance results are even more dramatic for mean slowdown. Figure 6 shows the mean slowdown under SRPT scheduling as compared with the traditional FAIR scheduling as a function of load. For lower loads the slowdowns are the same under the two scheduling policies. For system loads 0.5, the mean slowdown improves by a factor of 4 under SRPT over FAIR. Under a system load of 0.9, mean slowdown improves by a factor of 16.

Looking at the partly-open system model more closely we observe that mean response times are almost identical, regardless of the value of k. Figure 7 shows the performance of FAIR under a range of k values: $k = 1$, $k = 5$, and $k = 50$. It turns out that SRPT is even less sensitive to the choice of k. [3]

Throughout we show results for the open system model, however we have verified that all these results are almost identical under the partly-open system model with $k = 5$.

We conclude this section by once again considering the improvement of SRPT over FAIR, but this time in the case of a 100 Mbps uplink. Results are shown in Figure 8 for a system load of $\rho = 0.8$ under the Flash web server (i.e., 80 Mbps requested through a 100Mbps

[3] Having experimented with many k values, we find the following subtle trend as we increase k: When we initially increase k, we find that response times drop a bit. The reason is that by synchronizing the times at which requests are generated, so that they are generated only when a previous request completes, we do a better job of evening the burstiness in the number of connections at the server. As k increases further, however, the partly-open system starts to look like a closed system with zero think time. This has the effect of creating a near-one system load at all times, which causes response times to go up.

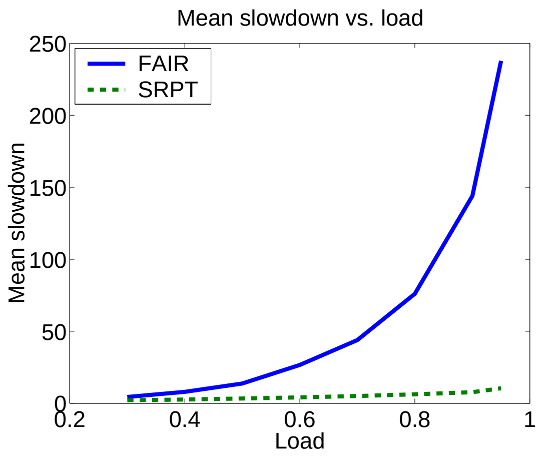


Figure 6: *Mean slowdown under SRPT versus FAIR as a function of system load, under trace-based workload, in LAN environment.*

uplink). We see that SRPT performs 5 times better than FAIR at a system load of 0.8. This is comparable to the improvement achieved in the case of the 10Mbps uplink.

In moving from a 10 Mbit network to a 100 Mbit network, observe that the arrival rate of jobs increases by a factor of 10, and the service requirement of jobs decreases by a factor of 10. Queueing theory thus tells us that we should expect mean response times to improve by a factor of 10 (as is easy to see by looking at the formula for an M/G/1 queue). However, in comparing Figure 5 and Figure 8, we note that the improvement in practice for both FAIR and SRPT is not as high as predicted by theory (more like a factor of 4–6). We suspect that the performance limits of other system elements (load) may be preventing the realization of the full 10 times improvement.

Another way to state the results in Figure 8 is to observe that the mean response time under FAIR with a system load of 0.5 is higher than the mean response time under SRPT with a system load of 0.95. Thus SRPT can be viewed as offering an increase in throughput of 45 Mbps under a 100 Mbps uplink, without sacrificing response time.

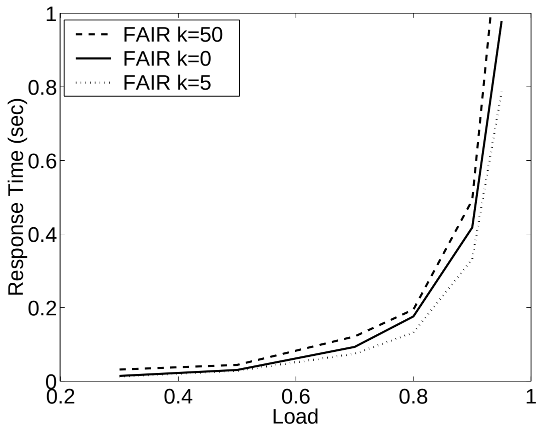


Figure 7: *Performance of FAIR shown for a partly-open system model, where $k = 1$, $k = 5$, and $k = 50$.*

The significant improvements of SRPT over FAIR observed in this section is easily explained. The time-sharing behavior of FAIR causes short requests to be delayed in part by long requests, whereas SRPT allows short requests to jump ahead of long requests. Since most requests are short requests, most requests see an order of magnitude improvement under SRPT. Another way to think of this is that SRPT is an opportunistic algorithm which schedules requests so as to minimize the number of outstanding requests in the system (it always works on those requests with the least remaining work to be done). By minimizing the number of outstanding requests in the system, Little's Law [28] tells us that SRPT also minimizes the mean response time.

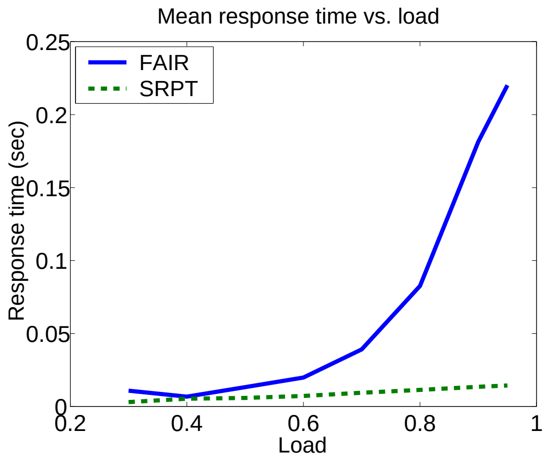
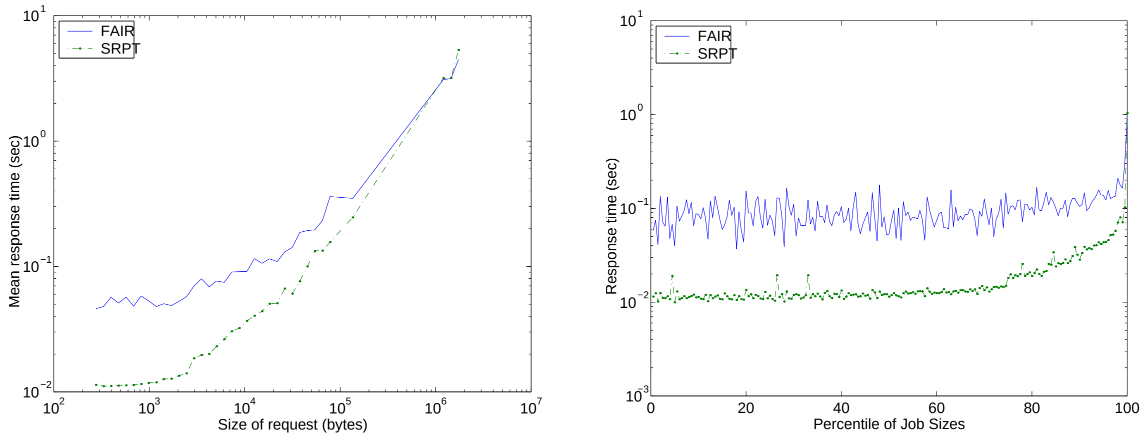


Figure 8: *Mean response time under SRPT versus FAIR as a function of system load, under trace-based workload, in LAN environment with server uplink bandwidth 100Mb/sec.*

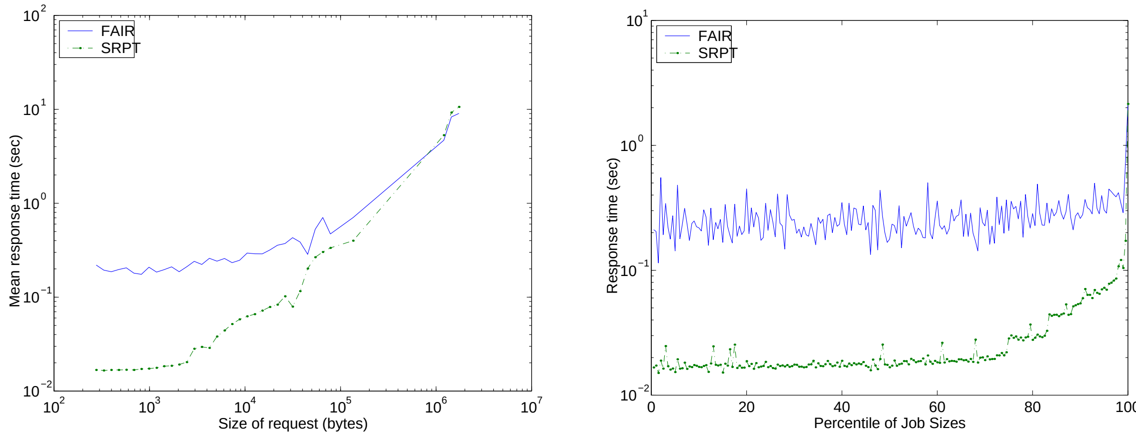
3.3 Performance of large requests under SRPT in LAN

The important question is whether the significant improvements in mean response time come at the price of significant unfairness to large requests. We will answer this question for both the open system model and the partly-open system model. We will look first at the case of 10 Mbps uplink and then at the case of 100 Mbps uplink.

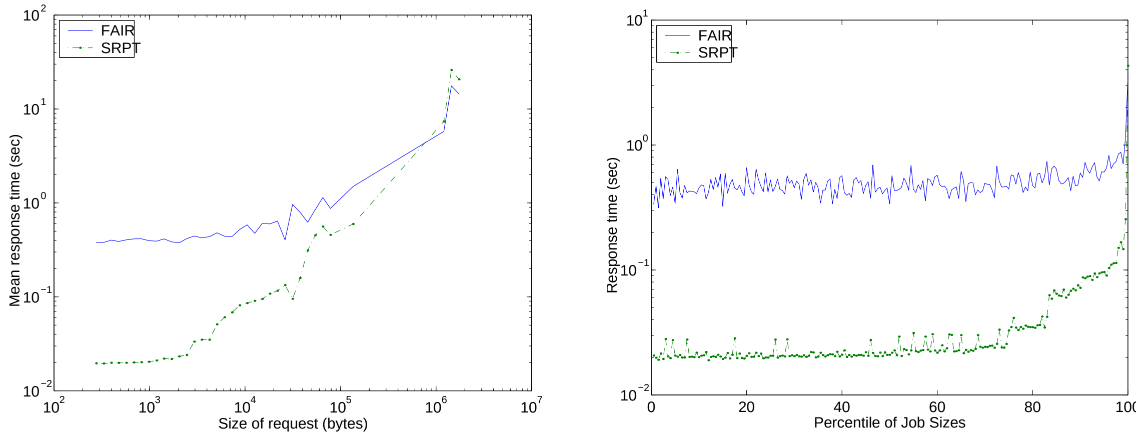
Figure 9 shows the mean response time as a function of request size, in the case where the system load is 0.6, 0.8, and 0.9 and the bandwidth on the server's uplink is 10 Mbps. In the left column of Figure 9, request sizes have been grouped into 60 bins, and the mean response time for each bin is shown in the graph. The 60 bins are determined so that each bin spans an interval $[x, 1.2x]$. It is important to note that the last bin actually contains only requests for the very biggest file. Observe that small requests perform far better under SRPT scheduling as compared with FAIR scheduling, while large requests, those $>$ 1 MB, perform only negligibly worse under SRPT as compared with FAIR scheduling. For example, under system load of 0.8 (see Figure 9(b)) SRPT scheduling improves the mean response times of small requests by a factor of close to 10, while the mean response time for the very largest size request only goes up by a factor of 1.2.



(a) system load = .6



(b) system load = .8



(c) system load = .9

Figure 9: *Mean response time as a function of request size under trace-based workload, shown for a range of system loads (corresponds to Figure 5(a)). The left column shows the mean response time as a function of request size. The right column shows the mean response time as a function of the percentile of the request size distribution.*

Note that the above plots give equal emphasis to small and large files. As requests for small files are much more frequent, these plots are not a good measure of the improvement offered by SRPT. To fairly assess the improvement, the right column of Figure 9, presents the mean response time as a function of the percentile of the request size distribution, in increments of half of one percent (i.e. 200 percentile buckets). From this graph, it is clear that at least 99.5% of the requests benefit under SRPT scheduling. In fact, the 80% smallest requests benefit by a factor of 10, and all requests outside of the top 1% benefit by a factor of > 5. For lower system loads, the difference in mean response time between SRPT and FAIR scheduling decreases, and the unfairness to big requests becomes practically nonexistent. For higher system loads, the difference in mean response time between SRPT and FAIR scheduling becomes greater, and the unfairness to big requests also increases. Even for the highest system load tested though (.95), there are only 500 requests (out of the 1 million requests) which complete later under SRPT as compared with FAIR. These requests are so large however, that the effect on their slowdown is negligible.

Results for the partly-open system model are similar to those in Figure 9, with slightly more penalty to the large jobs, but still hardly noticeable penalty. For the case of $k = 5$, with system load $\rho = 0.8$, the mean response time for the largest 1% of requests is still lower under SRPT (1.09 seconds under SRPT as compared with 1.12 seconds under FAIR). The very largest request has a mean response time of 9.5 seconds under SRPT versus 8.0 seconds under FAIR.

For the 100 Mb/sec experiments *all jobs*, large and small, preferred SRPT scheduling in expectation under all system loads tested.

Figure 10 shows the variance in response time for each request size as a function of the percentile of the request size distribution, for system load equal to 0.8. The improvement under SRPT with respect to variance in response time is 2 – 4 orders of magnitude for the 99.5% smallest files. The improvement with respect to the squared coefficient of variation (variance/mean^2) is about 30.

3.4 SRPT with only two priorities

Our SRPT algorithm is only a rough approximation of true SRPT since we use only 6 priority classes. An interesting question is how much benefit one could get with only 2 priority classes. That is, each request would simply be classified as being large or small, and would be prioritized accordingly.

To explore the performance of SRPT with only two

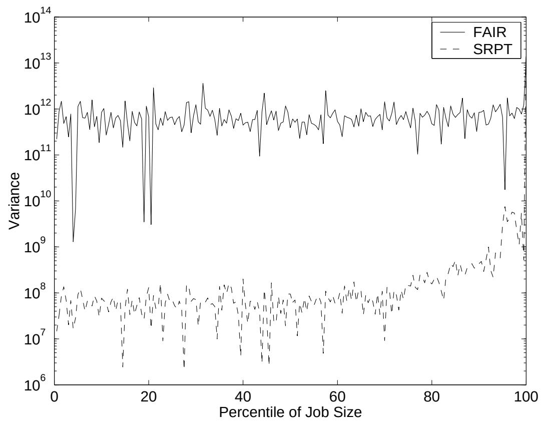


Figure 10: *Variance in response time as a function of the percentile of the request size distribution for SRPT as compared with FAIR, under trace-based workload with system load =* 0.8*, in a LAN.*

priority classes, we define *small* requests as the smallest 50% of requests and *large* requests as the largest 50% of requests (note, this is not the same thing as equalizing system load) The cutoff falls at 1K. We find that this simple algorithm results in a factor of 2.5 improvement in mean response time and a factor of 5 improvement in mean slowdown over FAIR. We also find that *all requests*, big and small, have lower expected response times under SRPT than under FAIR using this simple algorithm.

4 WAN setup and experimental results

To understand the effect of network congestion, loss, and propagation delay in comparing SRPT and FAIR, we also conduct WAN experiments. We perform two types of WAN experiments: (i) experiments using our LAN setup together with a WAN emulator (Section 4.1) and (ii) experiments using physically geographically-dispersed client machines (Section 4.2).

4.1 WAN emulator experiments

The two most frequently used tools for WAN emulation are probably NistNet [31] and Dummynet [35].

NistNet is a separate package available for Linux which can drop, delay or bandwidth-limit *incoming* packets. Dummynet applies delays and drops to both incoming and outgoing packets, hence allowing the user to create symmetric losses and delays. Since Dummynet is currently available for FreeBSD only we implement Dummynet functionality in form of a separate module for the Linux kernel. More precisely, we changed the `ip_rcv()` and the `ip_output()` function in the TCP-IP stack to intercept in- and out-going packets to create losses and delays.

In order to delay packets, we use the `timeout()` facility to schedule transmission of delayed packets. We recompile the kernel with `HZ=1000` to get a finer-grained millisecond timer resolution.

In order to drop packets we use an independent, uniform random loss model (as in Dummynet) which can be configured to a specified probability.

The experimental setup for our experiments is identical to that used for the LAN experiments (see Section 3.1) except that the WAN emulator functionality is now included in each client machine.

Figure 11 shows the effect of increasing the round-trip propagation delay (RTT) from 0 ms to 100 ms for FAIR and SRPT in the case of system load 0.9 and system load 0.7. Adding WAN delays increases response times by a constant additive factor on the order of a few RTTs for both FAIR and SRPT. The effect is that the relative improvement of SRPT over FAIR drops. Under system load $\rho = 0.9$, SRPT's improvement over FAIR drops from a factor of 4 when the RTT is 0 ms to a factor of 2 when the RTT is 100 ms. Under system load $\rho = 0.7$, the factor improvement of SRPT over FAIR drops from a factor of 2 to only 15%.

With respect to unfairness to large jobs, we find that any unfairness to large jobs decreases as the RTT is increased. The reason is obvious – any existing unfairness to large jobs is mitigated by the additive increase in delay imposed on both FAIR and SRPT.

Figure 12 assumes that the RTT is 0 ms and shows the effect of increasing the network loss from 0% to 10% under both FAIR and SRPT. Increasing loss has a more pronounced effect than increasing the RTT. We observe that the response times don't grow linearly in the loss rate. This is to be expected since TCPs throughput is inversely proportional to the square root of the loss. Under system load $\rho = 0.9$, SRPT's improvement over FAIR drops from a factor of 4 when loss is 0% to a factor of 25% when loss is 10%. Under system load $\rho = 0.7$, loss beyond 2% virtually eliminates any improvement of SRPT over FAIR.

With respect to unfairness to large jobs, we find that loss slightly increases the unfairness to the largest job under SRPT. The largest job performs 1.1 times worse under 3% loss, but 1.5 times worse under loss rates up to 10%. Nevertheless, even in a highly lossy environment, the mean response time for the largest 1% of jobs is still higher under FAIR as compared to SRPT.

Finally Figure 13 combines loss and delay. Since the effect of loss dwarfs the effect of propagation delay, the results are similar to those in Figure 12 with loss only.

4.2 Geographically-dispersed WAN experiments

We now repeat the WAN experiments using physically geographically-dispersed client machines. The experimental setup is again the same as that used for the LAN (see Section 3.1) except that this time the client machines are located at varying distances from the server. The table below shows the location of each client machine, indicated by its RTT from the server machine.

Location	Avg. RTT
IBM, New York	20ms
Univ. Berkeley	55ms
UK	90-100ms
Univ. Virginia	25ms
Univ. Michigan	20ms
Boston Univ.	22ms

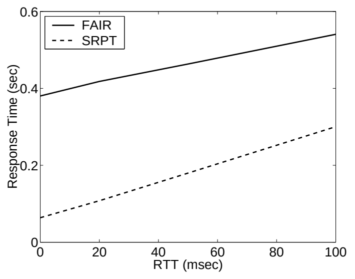
Unfortunately, we were only able to get accounts for Internet2 machines (schools and some research labs). The limitation in exploring only an Internet2 network is that loss and congestion may be unrealistically low.

Figure 14 shows the mean response time (in ms) as a function of system load for each of the six hosts. This figure shows that the improvement in mean response time of SRPT over FAIR is a factor of 8–20 for high system load (0.9) and only about 1.1 for lower system load (0.5).

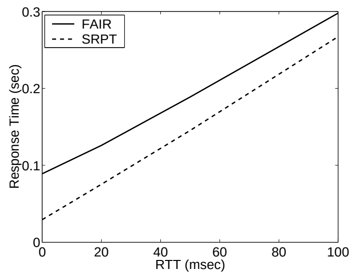
Figure 15(a) and 15(b) shows the mean response time of a request as function of the percentile the request size at a system load of 0.8 for the hosts at IBM and UK respectively. It's not clear from looking at the figures whether there is any starvation. It turns out that *all* request sizes have higher mean response time under FAIR, as compared with SRPT. For the largest file, the mean response time is almost the same under SRPT and FAIR. The reason for the lack of unfairness is the same as that pointed out in the WAN emulation experiments for the case of significant RTT, but near-zero loss.

We also measured the variance in response time in the WAN environment for a system load of 0.8. While the variance for FAIR stayed the same under the LAN and WAN environments, the variance for SRPT increased somewhat in the WAN environment due to mild losses. Still, however, the variance in response time under SRPT remains over an order of magnitude below that in FAIR, for a system load of 0.8.

We now compare the numbers in Figure 14 with

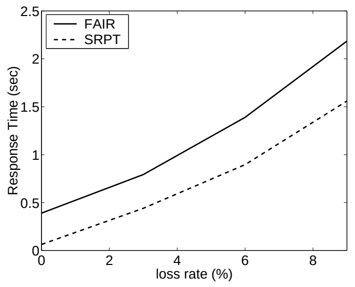


(a) system load $= 0.9$

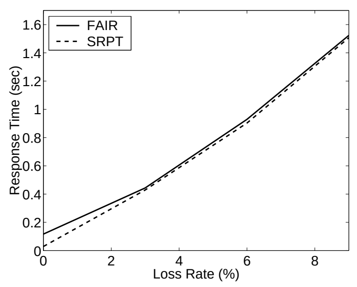


(b) system load $= 0.7$.

Figure 11: *Effect on SRPT and FAIR of increasing RTT from 0 ms to 100 ms.*

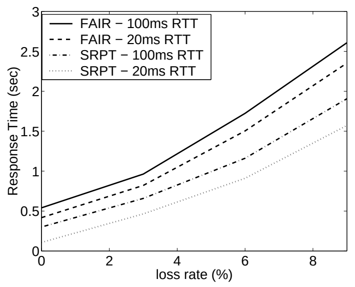


(a) system load $= 0.9$

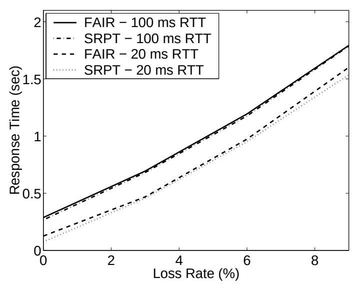


(b) system load $= 0.7$.

Figure 12: *Effect on SRPT and FAIR of increasing loss from 0% to 10%.*

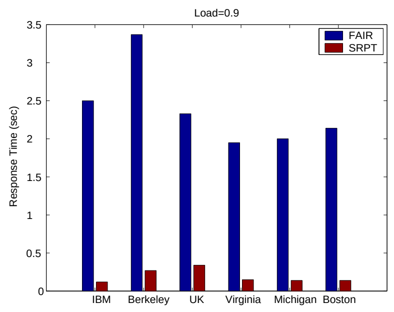


(a) system load $= 0.9$

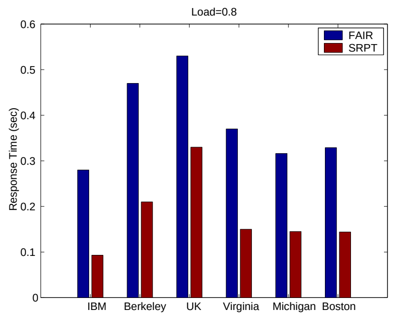


(b) system load $= 0.7$.

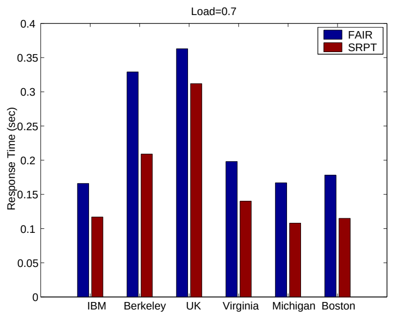
Figure 13: *Effect on SRPT and FAIR of increasing loss and delay.*



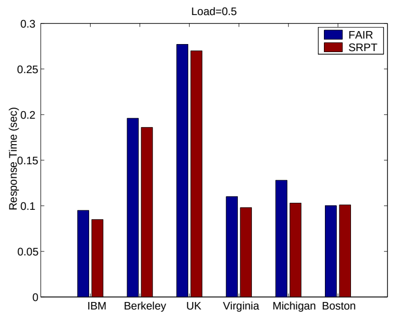
(a) system load 0.9



(b) system load 0.8

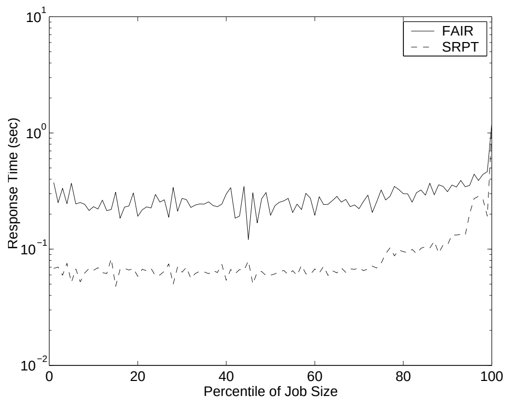


(c) system load 0.7

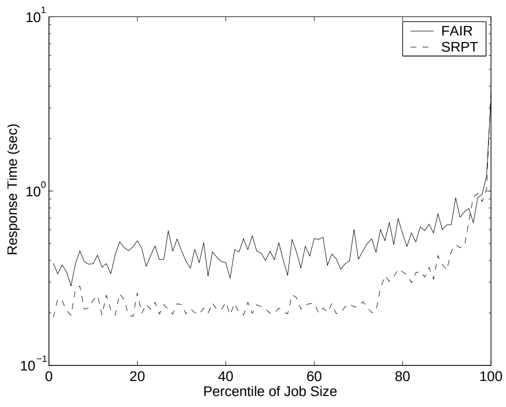


(d) system load 0.5

Figure 14: *Mean response time under SRPT versus FAIR in a WAN under system load (a) 0.9, (b) 0.8, (c) 0.7, and (d) 0.5.*



(a) IBM clients



(b) UK clients

Figure 15: *Response time as a percentile of request size under SRPT scheduling versus traditional FAIR scheduling at system load 0.8, measured for (a) the IBM host and (b) the UK host.*

those obtained using the WAN emulation. First of all, observe that for the case of system load 0.5, 0.7, and 0.8, the values of response time in Figure 14 are comparable with those obtained using the WAN emulator with propagation delay, but near-zero loss (compare with Figure 11).

Observe that the values of response time under system load 0.9 in Figure 14 are much higher than those for the WAN emulator for the case of FAIR but not for SRPT. The reason is that the WAN environment creates some variance in the system load. Thus an average system load of 0.9 translates to fluctuations ranging from 0.75 to 1.05, which means that there are moments of *transient overload*. Transient overload affects FAIR far worse than SRPT because the buildup in number of requests at the server during overload is so much greater under FAIR than under SRPT. Transient overload even occasionally results in a full SYN queue under FAIR. This means that incoming SYNs may be dropped, resulting in a timeout and retransmit. In the LAN environment where system load can be better controlled, we never experience SYN drops.

The trends shown in Figure 14 are in agreement with the WAN emulator experiments. To summarize: (i) The improvement of SRPT over FAIR is higher at higher system loads; (ii) The improvement of SRPT over FAIR is diminished for far away clients; (iii) The unfairness to large jobs under SRPT becomes non-existent as propagation delay is increased.

5 Why does SRPT work?

In this section we will look in more detail at where SRPT's performance gains come from and we explain why there is no starvation of long jobs.

5.1 Where do mean gains come from?

The high-level argument has been given before: SRPT is an opportunistic algorithm which schedules requests so as to minimize the number of outstanding requests in the system (it always works on those requests with the least remaining work to be done). By minimizing the number of outstanding requests in the system, Little's Law tells us that SRPT also minimizes the mean response time. In fact our measurements show that when the load is 0.7 the number of open connections is 3 times higher under FAIR than under SRPT. At load 0.9, this number jumps to 5 times higher. This corresponds to the improvement in mean response time of SRPT over FAIR.

Mathematically, the improvement of SRPT over FAIR scheduling with respect to mean response time has been derived for an M/G/1 queue in [7].

At an implementation level, while our implementation of SRPT, described in Section 2.1 is not an exact implementation of the SRPT algorithm, it still has the desirable properties of the SRPT algorithm: Short requests (those with small file size or small remaining file size) are separated from long requests and have priority over long requests. Note that our implementation does not interact illegally with the TCP protocol in any way: scheduling is only applied to those connections which are ready to send via TCP's congestion control algorithm.

The above discussion shows that one reason that SRPT improves over FAIR with respect to mean response times is because it allows short jobs to avoid time-sharing with long jobs. We now explore two other potential reasons for the improvement of SRPT over FAIR and eliminate both.

It has been stated that a problem for clients accessing a busy web server is that the web server's SYN queue might fill up, thereby preventing new connection requests from being handled. This in turn creates expensive timeouts for the clients (on the order of 3 seconds). Our measurements show in none of our experiments (except for one WAN experiment with high system load) does the SYN queue ever fill up – not under FAIR nor under SRPT – although the SYN queue is significantly fuller under FAIR than under SRPT for high system loads.

Another potential reason for SRPT's performance gains over FAIR is that by having multiple priority queues SRPT is essentially getting to use more buffering, as compared with the single transmit queue of FAIR (see Figure 2). It is possible that there could be an advantage to having more buffering inside the kernel, since under high system loads we have observed some packet loss (5%) within the kernel at the transmit queue under FAIR, but not under SRPT. To see whether SRPT is obtaining an unfair advantage, we experimented with increasing the length limit for the transmit queue under FAIR from 100 to 500, and then to 700, entirely eliminating the losses. This helped just a little — reducing mean response time from about 400ms to 350ms under FAIR. Still, performance was nowhere near that of SRPT.

5.2 Why are long requests not hurt?

It has been suspected by many that SRPT is a very unfair scheduling policy for large requests. The above results have shown that this suspicion is false for web workloads. It is easy to see why SRPT should provide huge performance benefits for the small requests, which get priority over all other requests. In this section we describe briefly why the large requests also benefit under SRPT, *in the case of a heavy-tailed workload*.

In general a heavy-tailed distribution is one for which

$$\Pr\{X > x\} \sim x^{-\alpha},$$

where $0 < \alpha < 2$. A set of request sizes following a heavy-tailed distribution has some distinctive properties:

1. Infinite variance (and if $\alpha \leq 1$, infinite mean). (In practice, variance is not really infinite, but simply very high, since there is a finite maximum request size).

2. The property that a tiny fraction (usually $< 1\%$) of the very longest requests comprise over half of the total system load. We refer to this important property as the **heavy-tailed property**.

The lower the parameter α, the more variable the distribution, and the more pronounced is the heavy-tailed property, *i.e.* the smaller the fraction of long requests that comprise half the system load.

Request sizes are well-known to follow a heavy-tailed distribution [13, 15]. Our traces also have strong heavy-tailed properties. (In our trace the largest $< 3\%$ of the requests make up $> 50\%$ of the total system load.)

Consider a workload where request sizes exhibit the *heavy-tailed property*. Now consider a large request, in the 99%-tile of the request size distribution. This request will actually do much better under SRPT scheduling than under FAIR scheduling. The reason is that this big request only competes against 50% of the system load under SRPT (the remaining 50% of the system load is made up of requests in the top 1%-tile of the request size distribution) whereas it competes against 100% of the system load under FAIR scheduling. The same argument could be made for a request in the 99.5%-tile of the request size distribution.

However, it is not obvious what happens to a request in the 100%-tile of the request size distribution (i.e. the largest possible request). It turns out that, provided the system load is not too close to 1, the request in the 100%-tile will quickly see an idle period, during which it can run. As soon as the request gets a chance to run, it will quickly become a request in the 99.5%-tile, at which time it will clearly prefer SRPT. For a mathematical formalization of the above argument, in the case of an M/G/1 queue, we refer the reader to [7].

Despite our understanding of the above theoretical result, we were nevertheless still surprised to find that results in practice matched those in theory – i.e., there was little if any unfairness to large jobs. It is understandable that in practice there should be more unfairness to large jobs since large requests pay some additional penalty for moving between priority queues.

6 Previous Work

There has been much literature devoted to improving the response time of web requests. Some of this literature focuses on reducing network latency, e.g. by caching requests ([20], [11], [10]) or improving the HTTP protocol ([32]). Other literature works on reducing the delays at a server, e.g. by building more efficient HTTP servers ([19], [33]) or improving the server's OS ([17], [6], [26], [30]).

In the remainder of this section we discuss only work on *priority-based* or *size-based* scheduling of requests. We first discuss related implementation work and then discuss relevant theoretical results.

Almeida et. al. [1] use both a user-level approach and a kernel-level implementation to prioritizing HTTP requests at a web server. The *user-level* approach in [1] involves modifying the Apache web server to include a Scheduler process which determines the order in which requests are fed to the web server. This modification is all in the application level and therefore does not have any control over what the OS does when servicing the requests. The *kernel-level* approach in [1] simply involves setting the priority of the process which handles a request in accordance with the priority of the request. Observe that setting the priority of a process only allows very coarse-grained control over the scheduling of the process, as pointed out in the paper. The user-level and kernel-level approaches in this paper are good starting points, but the results show that more fine-grained implementation work is needed. For example, in their experiments, the high-priority requests only benefit by 20% and the low priority requests suffer by up to 200%.

Another attempt at priority scheduling of HTTP requests which deals specifically with SRPT scheduling at web servers is that of Crovella et. al. [14]. This implementation does not involve any modification of the kernel. The authors experiment with connection scheduling at the *application level* only. They design a specialized Web server which allows them to control the order in which `read()` and `write()` calls are made, but does not allow any control over the low-level scheduling which occurs inside the kernel, below the application layer (*e.g.*, control over the order in which socket buffers are drained). Via the experimental Web server, the authors are able to improve mean response time by a factor of up to 4, for some ranges of system load, but the improvement comes at a price: *a drop in* *throughput by a factor of almost 2*. The explanation, which the authors offer repeatedly, is that scheduling at the application level does not provide fine enough control over the order in which packets enter the network. In order to obtain enough control over scheduling, the authors are forced to limit the throughput of requests. This will not be a problem in our paper. Since the scheduling is done at the kernel, we have absolute control over packets entering the network. Our performance improvements are greater than those in [14] and do not come at the cost of any decrease in throughput.

The papers above offer coarser-grained implementations for priority scheduling of connections. Very recently, many operating system enhancements have appeared which allow for finer-grained implementations of priority scheduling [21, 34, 2, 3].

Several papers have considered the idea of SRPT scheduling in theory.

Bender et. al. [9] consider size-based scheduling in web servers. The authors reject the idea of using SRPT scheduling because they prove that SRPT will cause large files to have an arbitrarily high *max slowdown*. However, that paper assumes a worst-case adversarial arrival sequence of web requests. The paper goes on to propose other algorithms, including a theoretical algorithm which does well with respect to max slowdown and mean slowdown.

Roberts and Massoulie [36] consider bandwidth sharing on a link. They suggest that SRPT scheduling may be beneficial in the case of heavy-tailed (Pareto) flow sizes.

Lastly, Bansal and Harchol-Balter [7] investigate SRPT scheduling analytically for an M/G/1/SRPT queue (Poisson arrivals and general service times). We discussed these theoretical results in Section 5.

7 Conclusion and Future work

This paper demonstrates that the delay at a busy server can be greatly reduced by SRPT-based scheduling of the bandwidth that the server has purchased from its ISP. We show further that the reduction in server delay often results in a reduction in the client-perceived response time.

In a LAN setting, our SRPT-based scheduling algorithm reduces mean response time significantly over the standard FAIR scheduling algorithm. In a WAN setting the improvement is still significant for very high system loads, but is far less significant at moderate system loads.

Surprisingly, this improvement comes at no cost to large requests, which are hardly penalized, or not at all penalized. Furthermore these gains are achieved under no loss in byte throughput or request throughput.

Our current setup involves only *static* requests. In future work we plan to expand our technology to schedule cgi-scripts and other *non*-static requests. Determining the size (processing requirement) of non-static requests is an important open problem, but companies are making excellent progress on predicting the size of dynamic requests. We propose additionally to deduce the size of a dynamic request as it runs. The request will initially be assigned high priority, but its priority will decrease as it runs.

Our current setup considers the bottleneck resource at the server to be the server's limited bandwidth purchased from its ISP, and thus we do SRPT-based scheduling of that resource. In a different application (e.g. processing of cgi-scripts) where some other resource was the bottleneck (e.g., CPU), it might be desirable to implement SRPT-based scheduling of that resource.

Although we evaluate SRPT and FAIR across many system loads, we do not in this paper consider the case of overload. This is an extremely difficult problem both analytically and especially experimentally. Our preliminary results show that in the case of *transient overload* SRPT outperforms FAIR across a long list of metrics, including mean response time, throughput, server losses, etc.

Our SRPT solution can also be applied to server farms. Again the bottleneck resource would be the limited bandwidth that the web site has purchased from its ISP. SRPT-based scheduling would then be applied to the router at the joint uplink to the ISP.

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