Implementation of SRPT Scheduling in Web Servers

Mor Harchol-Balter* Nikhil Bansal Bianca Schroeder Mukesh Agrawal

School of Computer Science

Carnegie Mellon University

Pittsburgh, PA 15213

⟨harchol,nikhil,bianca,mukesh⟩@cs.cmu.edu

Abstract

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 quick, 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 use the Linux operating system and the Apache web server. All experiments are also repeated using the Flash Web server. Experiments are run under both trace-based workloads and those generated by a Web workload generator.

Results indicate that SRPT-based scheduling of connections yields significant reductions in mean response time, mean slowdown, and variance in response time at the Web server. Most significantly, and counter to intuition, the *large requests* are only negligibly penalized (or not at all penalized) as a result of SRPT-based scheduling.

*This research is funded by Cisco Systems via a grant from the Pittsburgh Digital Greenhouse 00-1 and by NSF-ITR 99-167 ANI-0081396. Equipment was also provided by the Parallel Data Lab.

1 Introduction

Today's busy Web servers may be servicing hundreds of requests at the same time. This can cause large queueing delays at the Web server, or close to it. Our overall goal in this paper is to minimize the queueing delay at a Web server.

The idea is simple. Recent measurements [20] have suggested that the request stream at most Web servers is dominated by *static* requests, of the form "Get me a file." The question of how to service static requests quickly is the focus of many companies *e.g.*, Akamai Technologies, and much ongoing research. For static requests, the *size of the request* (i.e. the time required to service the request) is well-approximated by the size of the file, which is well-known to the server. Thus far, (almost) no companies or researchers have made use of this information. We propose to use the knowledge of the size of the request to affect the scheduling order in which requests are serviced by the Web server, and in this way minimize the queueing delay at the Web server.

Traditionally, requests at a Web server are scheduled independently of their size. The requests are time-shared, with each request receiving a *fair share* of the Web server resources. We propose, instead, *unfair scheduling*, in which priority is given to *short* requests, or those requests which have *short remaining time*, in accordance with the well-known scheduling algorithm Shortest-Remaining-Processing-Time-first (SRPT).

There is an obvious reason why *unfair scheduling* is not used. Unfair scheduling seems to imply that some requests will "starve," or at least be harshly penalized (see Section 2 for a list of references to this effect). This intuition is usually true. However, we have a new theoretical paper, [21], which proves that in the case of (heavy-tailed) Web workloads, this intuition falls apart. In particular, for Web workloads, even the largest requests are *not* penalized (or negligible penalized) by SRPT scheduling. These new theoretical results have motivated us to reconsider "unfair" scheduling.

It's not immediately clear what SRPT means in the context of a Web server. The SRPT scheduling policy is well-understood in the context of a single-queue, single-resource system [27]: at any moment in time, give the full resource to that one request with the shortest remaining processing time requirement. However a Web server is not a single-resource system; thus it would be highly inefficient to schedule only *one* request at a time to run in the Web server. Furthermore, it is not even obvious *which* of the Web server's resources need to be scheduled.

As one would expect, it turns out that scheduling is only important at the *bottleneck resource*. In practice it is very common that this bottleneck resource is the *bandwidth* on the access link out of the Web site. Access links to Web sites (T3, OC3, etc.) cost thousands of dollars per month, whereas CPU is cheap in comparison. Thus the CPU is rarely the bottleneck resource (since it is inexpensive to add more CPU). Likewise disk utilization remains low since most files end up in the cache. We have experimented with a Web server connected to a 100Mbps access link and found that the access link was the bottleneck. However, in this paper we purposely use a 10Mb/sec link out of our Web server, simply because it makes it easy to saturate the link in experimentation. Throughout our experiment, the measured CPU utilization and disk utilization remain extremely low. It is important to note that although we concentrate on the case where the network bandwidth is the bottleneck resource, all the ideas in this paper can also be applied to the case where the CPU is the bottleneck — in which case SRPT scheduling is applied to the CPU.

Since the network is the bottleneck resource, we try to apply the SRPT idea at the level of the network. Our idea is to control the order in which socket buffers are drained. Recall that for each (non-persistent) request a connection is established between the client and the Web server, and corresponding to each connection, there is a socket buffer on the Web server end into which the Web server writes the contents of the file requested. Traditionally, the different socket buffers are drained in Round-Robin Order (each getting a fair share of the bandwidth of the outgoing link). 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. In Section 3 we describe the implementation issues involved in implementing priority scheduling of socket buffers.

Our experiments use the Linux operating system and the Apache Web server. For completeness we also repeat all experiments using the Flash Web server [23] which is known for speed. **For lack of space, we have only included the Apache plots in this abstract; the Flash plots are in the associated technical report [22]**. In order to perform statistically meaningful experiments, our clients use a request sequence taken from a Web trace, or alternatively, a request sequence generated by a Web workload generator (See Section 4.2). This request sequence is controlled so that the server load remains below 1 and so that the same experiment can be repeated at different server loads (the server load is the load at the bottleneck device – in this case the network link out of the Web server). The experimental setup is detailed in Section 4.

Each experiment is repeated in two ways:

- Under the standard Linux o.s. (fair-share draining of socket buffers) with an unmodified Web server. We call this **FAIR scheduling**.
- Under the modified Linux o.s. (SRPT-based draining of socket buffers) with the Web server modified only to update socket priorities. We call this **SRPT-based scheduling**.

We experiment with different Web workloads, different system loads, and different lengths of experiments. For each experiment we measure mean response time, variance in response time, mean slowdown, and variance in slowdown. We also measure the mean response time as a function of the request size, to examine the question of whether the mean response time for just the largest requests is higher under SRPT-based scheduling as compared with FAIR scheduling. We find the following results, detailed in Section 5:

- SRPT-based scheduling decreases mean response time by a factor of 3 – 8 for loads greater than 0.5 under Apache. The corresponding factor improvement under Flash is 2 – 5.

- SRPT-based scheduling decreases the mean slowdown by a factor of 4 – 16 for loads greater than 0.5 under Apache. The corresponding factor improvement under Flash is 2 – 7.

- SRPT-based scheduling helps small requests a lot, while negligibly penalizing large requests. For example, under a load of 0.8, our experiments show that 80% of the requests improve by a factor of 10 under SRPT-based scheduling, with respect to mean response time, and all but the top 0.5% of the requests improve by a factor of over 5 under SRPT-based scheduling, with respect to mean response time. Only the largest 0.1% of requests suffer an increase in mean response time under SRPT-based scheduling (by a factor of only 1.2). These numbers hold for both Flash and Apache.

- The variance in the mean response time for most requests under SRPT-based scheduling is far lower for *all* requests, in fact two orders of magnitude lower for most requests. This statement holds for both Flash and Apache.

- *SRPT-based scheduling (as compared with FAIR scheduling) does not have any effect on the network throughput or the CPU utilization (under both Flash and Apache).*

In Section 6.1 we provide some theoretical justification for why SRPT scheduling improves upon FAIR scheduling along all these metrics.

Any nice result leads one to ask whether it can be achieved with less work. In Section 3 we investigate whether the benefits of SRPT can be achieved more easily. Our key observation is that the supposedly-fair draining of socket buffers in standard Linux is in fact not quite fair. Specifically, the particular structure of queues in the Linux kernel inadvertently creates some bias against *small requests*, thus being *unfair* to *small requests*. The above observation about Linux lead us to propose a "quick-fix" to Linux, with the following results under both Apache and Flash:

- The performance of the smallest 50% of the requests improves by a factor of 10 with respect to mean response time under the "quick-fix."

- The largest 50% of the requests are not negatively impacted whatsoever by the "quick-fix." In fact, many benefit.

The "quick-fix" and its results are discussed in Section 7.

It is important to realize that this paper is just a prototype to illustrate the power of using SRPT-based scheduling. In Section 9, we elaborate on broader applications of SRPT-based scheduling, including the application of SRPT-based scheduling to other resources, e.g. CPU, to cgi-scripts and other non-static requests, and finally the application of SRPT-based scheduling to routers throughout the Internet.

2 Relevant Previous Work

There has been much work on improving the performance of Web servers servicing static requests. However in most of this work, the goal has been to increase server throughput. That is not our goal. We maintain the same server throughput while improving the client experience (the client's response time). We first discuss related implementation work and then discuss relevant theoretical results.

Many recent papers have dealt with the issue of how to obtain differentiated quality of service in Web servers, via priority-based scheduling of requests. These papers are generally interested in providing different levels of service to different customers, rather than using a size-based scheme like our own. Various ideas have been tried to implement such prioritization schemes. We describe these below.

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 o.s. 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, the high-priority requests only benefit by up to 20% and the low priority requests suffer by up to 200%.

Another attempt at priority scheduling of HTTP requests is more closely related to our own because it too deals with SRPT scheduling at Web servers [10]. 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 close to 4, for some ranges of 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 [10] 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 [14, 25, 2, 3].

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

Bender, Chakrabarti, and Muthukrishnan [7] 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 [26] consider bandwidth sharing on a link and survey various scheduling policies. They suggest that SRPT scheduling may be beneficial in the case of a heavy-tailed (Pareto) flow sizes.

The primary theoretical motivation for this paper, comes from our own paper, [21]. This is a theoretical paper on the starvation properties of SRPT scheduling. The authors prove bounds on how much worse a request could perform under SRPT scheduling as compared with PS (processor-sharing, a.k.a. fair-share time-sharing) scheduling, within an M/G/1 setting. The authors also corroborate their results using a trace-driven simulation with real arrival stream. The authors prove that the penalty to large requests under SRPT (as compared with PS) is not severe. In particular, they show that for a large range of *heavy-tailed* (Pareto) distributions, *every single request*, including the very largest request, performs better under SRPT scheduling as compared with PS scheduling. The case of heavy-tailed request size distributions is important because heavy-tailed distributions have been shown to arise in many empirical computer workloads [19, 16, 8, 18, 24]. In particular measurements of *Web file sizes* and *HTTP request times* have been shown to be heavy-tailed [6]. We use the theoretical results in [21] to corroborate the results in this paper.

The general idea of size-based scheduling for heavy-tailed workloads has also been explored in arenas other than Web servers. Shaikh, Rexford, and Shin [28] discuss routing of IP flows (which have heavy-tailed size distributions) and propose routing long flows differently from short flows. Harchol-Balter [17] considers scheduling in distributed server systems where requests are not preemptible, request sizes are unknown, and where the workload is heavy-tailed. She proposes size-based scheduling using an algorithm for gradually learning sizes.

3 Implementation of prioritized socket draining

In Section 3.1 we explain how socket draining works in standard Linux. In Section 3.2 we describe how to achieve priority queueing in Linux versions 2.2 and above. Section 3.3 describes the implementation end at the Web server and also deals with the algorithmic issues such as choosing good *priority classes* and setting and updating priorities. Section 3.3 also describes an additional complexity: One problem with size-based queueing is 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. Section 3.3.2 describes our solution to this problem. Lastly, in Section 3.4 we motivate our implementation design choices.

3.1 Default Linux configuration

Figure 1 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*[1] "priority queue", into which *all* streams feed. In the abstract, these flows take equal turns feeding into the priority queue. In practice, this is not quite the case. However, we have found (via tcpdump) that the regularities of TCP end up creating a close to idyllic state where flows share fairly on short timescales.

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.

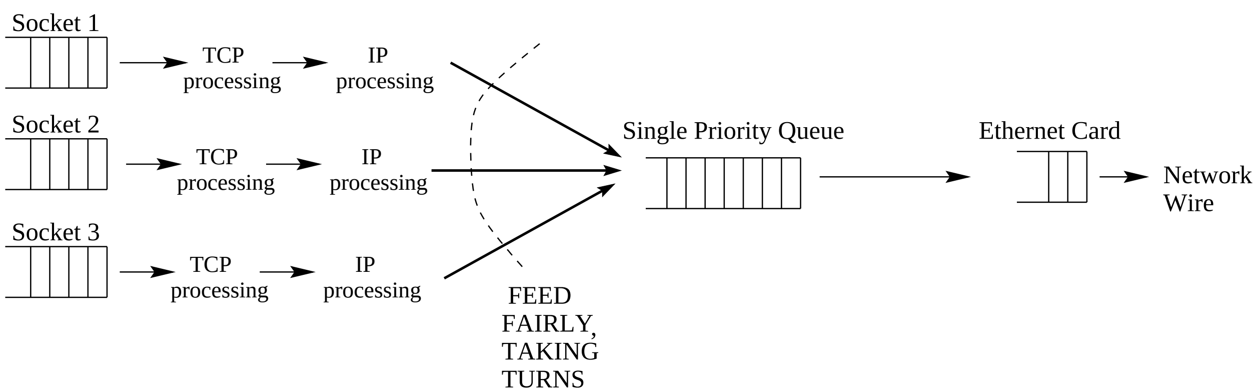


Figure 1: *Data flow in Standard Linux. The important thing to observe is that there is a* single *priority queue into which all connections drain fairly.*

3.2 How to achieve priority queueing in Linux

To implement SRPT we need more priority levels. Fortunately, it is relatively easy to achieve 16 priority queues (bands), as follows:

First, we 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] userspace tool to switch the device queue from the default 3-band queue to the 16-band prio queue.

Figure 2 shows the flow of data in Linux after the above modification: This understanding was obtained via experiments, reading the code, and by reading the following papers: [14, 25, 2, 3].

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

Again, 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 are kept separate. Finally, 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 to flow if priority queues 0 through $i - 1$ are all empty.

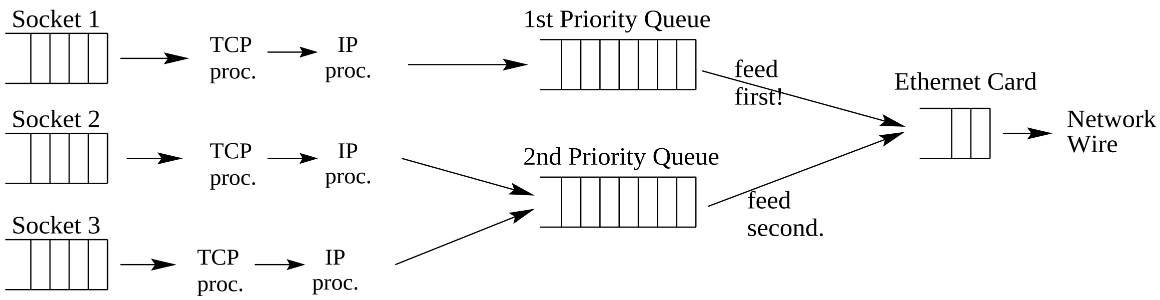


Figure 2: *Flow of data in Linux with priority queueing. It is important to observe that there are several priority queues, and queue i is serviced only if all of queues 0 through $i - 1$ are empty.*

Besides the above modifications to Linux, there are a few more modifications necessary to really make priority queueing possible. In the remainder of this subsection we describe some further low-level modifications which are necessary. In Section 3.3.2 we describe a higher-level modification which is necessary.

The following is a detailed account of some of our experiences in implementing priorities and some lessons learned. We hope that this will be useful to other implementors.

After making the above described modifications to Linux, we tried a simple experiment: We opened two TCP connections and flooded both connections with data. Specifically, we repeatedly wrote 1K of data into each socket within an infinite write loop (note that the writes are non-blocking). We gave high priority to connection 1 and low priority to connection 2. We expected that the packets on the wire would all be connection 1 packets. In truth, however, only 51% of the packets on the wire were connection 1 packets and 49% were connection 2 packets.

We repeated the above experiment, but this time with two UDP connections and saw a $60\%/40\%$ split between connection 1 packets and connection 2 packets.

We next observed that when we increased the number of connections from 2 to 10, we always achieved the desired $100\%/0\%$ ratio, however we desired a solution that did not require more than 2 connections.

After various other such experiments, we reached the conclusion that the critical parameter in achieving prioritized queueing is the size of the server's send socket buffer. All the experiments in this paper have been run with the server's send socket buffer increased by a factor of 3. In this mode, we are able to get *full* priority scheduling ($100\%/0\%$ ratio of connection 1 packets to connection 2 packets).

Note that the changes to the sender's send socket buffer are not absolutely necessary for the experiments in the paper, since in these experiments we have many simultaneous connections (rather than just 2). The changes in the sender's send socket buffer do not influence mean performance with respect to the experiments in this paper, however, they do help reduce starvation slightly.

3.3 Modifications to the Web server and Algorithmic issues in approximating SRPT

To use priority-based queueing, socket priorities must be initialized. This is done using the `setsockopt()` system call, based on the initial size of the request. Later the socket priorities must be updated, in agreement with the remaining size of the file. These functions are executed within the Web server itself (see Section 3.4 for an explanation of this design choice).

3.3.1 Size cutoffs

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

It turns out that the way in which request sizes are partitioned among these priority levels is somewhat important with respect to the performance of the Web server. We've spent some time searching the space of cutoffs and have come up with some good *rules-of-thumb* which apply to the heavy-tailed Web workloads. The reader not familiar with heavy-tailed workloads will benefit by first reading Section 6.1. Denoting the cutoffs by $x_1 < x_2 < \ldots < x_n$:

- The lowest size cutoff x_1 should be such that about 50% of jobs have size smaller than x_1. The intuition here is that the smallest 50% of jobs 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 jobs have size $> x_n$. This is necessary to prevent the largest jobs 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 5 priority classes to approximate SRPT. Using more improved performance only slightly.

3.3.2 Additional fixes necessary

It seems that one should now be able to execute prioritized size-based scheduling by simply assigning sockets for small requests to priority queues with high priority (these have low band numbers) and assigning sockets for large requests to low priority queues (these have high band numbers). It turns out, however that this is not sufficient to get good performance improvement. The reason is somewhat subtle. A lot of the time for servicing a request is made up by connection startup time: specifically, the sending of the SYN ACK by the server. The Linux o.s. sends all such control commands to one particular priority band (band 0). This is not under our control. It is important that when assigning priority bands to sockets 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 SYN ACKs always have highest priority.

This fix makes connection startup time very low, so that it doesn't dominate the response times of small files.

Note that by default Linux sends *all* packets, including SYN ACKs, to the same single priority queue. Thus SYN ACKs have to wait in a long queue, which can result in about 120ms startup time for all requests. This 120ms startup time gets added into the response time for short requests, which keeps short requests from doing well.

By keeping the SYN ACKs in their own priority queue, this startup cost can virtually eliminated. This observation was also made very recently in [5]. This fix, *together with* giving short requests priority over long ones, enables the performance of short requests to improve immensely, which is at the heart of our observed improvements. Observe also that giving highest priority to the SYN ACKs does not negatively impact the performance of requests since the SYN ACKs themselves make up only a negligible fraction of the total load.

3.3.3 The final algorithm

Our SRPT-like algorithm is thus as follows:

1. Priorities 1, 2, 3, 4, and 5 are associated with size ranges, where 1 denotes highest priority.
2. When a request arrives, it is given a socket with priority 0. This is an *important* detail which allows SYN ACKS to travel quickly. This was explained in Section 3.3.2.
3. 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.
    - Priority 1 is used for files of size $\leq 1K$.
    - Priority 2 is used for files of size between 1K and 2K.
    - Priority 3 is used for files of size between 2K and 5K.
    - Priority 4 is used for files of size between 5K and 50K.
    - Priority 5 is used for files of size greater than 50K.

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

3.4 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` system calls which must be made and the low system call overhead in Linux. A `setsockopt` is only called when a request's priority changes. This happens at most 5 times, and only for the very largest of the file requests.

The modifications to the server code are minimal. Based on our experience, a programmer familiar with a web server should be able to make the necessary modifications in just a couple of hours.

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.

4 Experimental Setup

4.1 Architecture

Our experimental architecture involves two machines each with an Intel Pentium III 700 MHz processor and 256 MB RAM, running Linux 2.2.16, and connected by a 10Mb/sec full-duplex Ethernet connection. The Apache Web server is running on one of the machines. The other machine hosts up to 200 clients which send requests to the Web server.

4.2 Workload

The clients' requests are generated either via a *Web workload generator* (we use a modification of `Surge` [6]) or via *traces*. *Throughout this paper, all results shown are for a trace-based workload*. We have included in the Appendix the *same*, *full set* of results for the `Surge` workload.

4.2.1 Traces

The traces come from a day in the Soccer World Cup 1998, and were downloaded from the Internet Traffic Archive [15]. These Soccer World Cup traces include virtually no non-static requests. An entry in the trace includes: (1) the time the request was received at the server, (2) the size of the request in bytes, (3) the GET line of the request, (4) the error code, as well as other information. In our experiments, we use the trace to specify the time the client makes the request (this is entry 1 above) and the size in bytes of the request (this is entry 2 above).

We used only 7 minutes of the trace (from 10:00:20 p.m. to 10:07 p.m.). Note: after completing all the experiments, we reran most of the experiments for a 1 hour period, rather than just 7 minutes. There was no noticeable change in the results.

Some statistics about our trace workload: The mean file size requested is 5K bytes. The min size file requested is a 41 byte file. The max size file requested is a 2.020644 MB file. There are approximately 90,000 requests made during the 7 minutes, which include requests for over a thousand *different* files. The distribution of the file sizes requested fits a heavy-tailed Pareto distribution. The the largest $< 3\%$ of the requests make up $> 50\%$ of the total 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.

4.2.2 Web workload generator

We also repeated all experiments using a Web workload generator. These results are shown in the Appendix.

4.2.3 Determination of System Load

The system load is an extremely important criterion in our experiments. Since the bottleneck resource is the network bandwidth on the outgoing link of the server, we define the system load to be the ratio of the bandwidth used on average and the maximum bandwidth available . Thus if our arrival sequence is such that 8Mb of bandwidth is utilized on a 10Mb/s link, we say that our system is running under load 0.8.

To create a particular load, we simply scale the interarrival times in the trace's request sequence. The scaling factor for the interarrival times is derived both analytically and empirically.

The analytical method is simple: Since we know the average number of bytes per request, we can estimate the fraction of the total bandwidth that would be used under any arrival rate. However this analysis alone does not allow us to obtain a very accurate estimate of load, since the data transfered over a link includes the size of the various network protocol headers. Moreover we cannot be sure that the maximum bandwidth available is exactly 10Mb/s. So our load estimate might be inaccurate.

To obtain a very accurate estimate of the load, we use the following empirical method. We start with a small arrival rate and measure the network bandwidth utilization (rather than calculating it). Then we increase the rate slowly and again measure the bandwidth. The bandwidth increases linearly with the arrival rate, but then stops increasing when the arrival rate reaches a value at which the system load first becomes 1. We note this critical arrival rate. To obtain a load $\rho < 1$ we just set the arrival rate to ρ times the critical arrival rate.

Throughout our experiment, we verify that our estimates for loads using both the analytical and emipirical methods agree, since even a small absolute difference (say 0.8 as opposed to 0.9) can create a lot of difference in the results.

5 Experiments and Experimental Results

We run a series of experiments comparing:

Standard Linux with FAIR Scheduling versus **Linux with our SRPT-based Priority Scheme**

Each experiment is run for 10 minutes, to ensure that all jobs complete. 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 [12, 4, 16]. Mean slowdown is the average of the slowdown of each of the requests.
- *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.

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

- In all of our experiments the network was the bottleneck resource. CPU utilization during our experiments ranged from 1% in the case of low load to 5% in the case of high load.
- The measured throughput and bandwidth utilization under the experiments with SRPT scheduling is *identical* to that under the same experiments with FAIR scheduling, and in both cases the maximum possible throughput is achieved, given the request sequence.
- 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. Observe that the overhead due to updating priorities of sockets is insignificant, given the small number of priority classes that we use.

Figure 3 shows the mean response time under SRPT scheduling as compared with the traditional FAIR scheduling as a function of load. For lower loads the mean response times are similar under the two scheduling policies. However for loads > 0.5, the mean response time is a factor of 3 – 8 lower under SRPT scheduling. These results are in agreement with our theoretical predictions in [21].

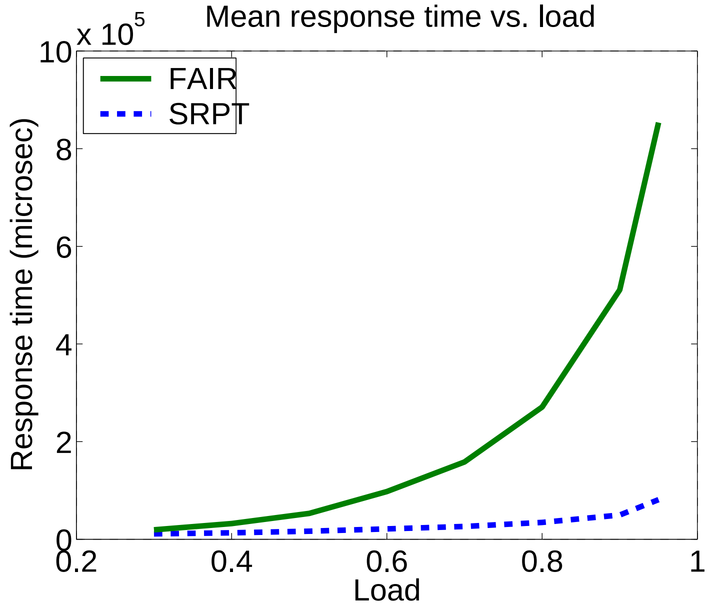


Figure 3: *Mean response time under SRPT scheduling versus traditional FAIR scheduling as a function of system load, under trace-based workload.*

The results are even more dramatic for mean slowdown. Figure 4 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. However for loads > 0.5, the mean slowdown is a factor of 4 – 16 lower under SRPT-based scheduling as compared with FAIR scheduling.

The important question is whether the significant improvements in mean response time come at the price of significant unfairness to large requests. Figure 5 shows the mean response time as a function of request size, in the case where the load is 0.6, 0.8, and 0.9. In the left column of Figure 5, 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 load of 0.8 (see Figure 5(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 largest size request only goes up by a factor of 1.2. The right column of Figure 5 is identical in content to the left column, but this time we see 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.

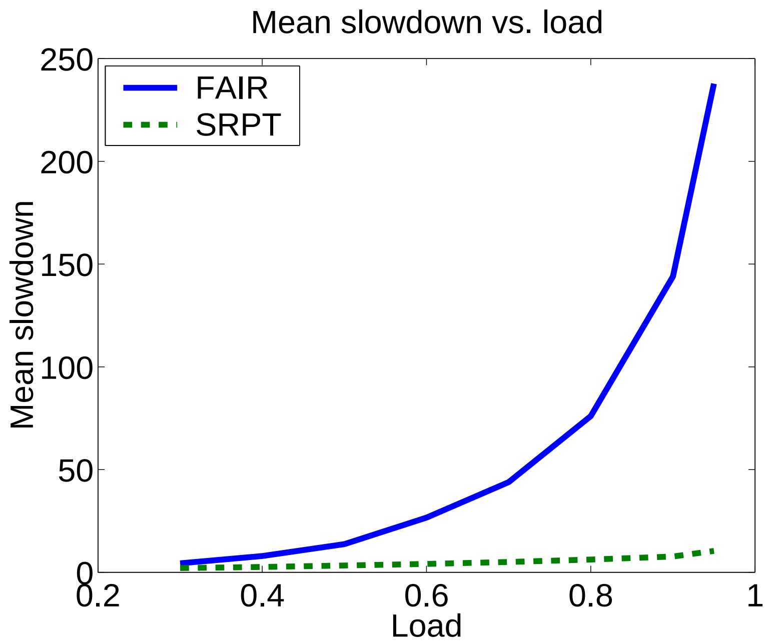


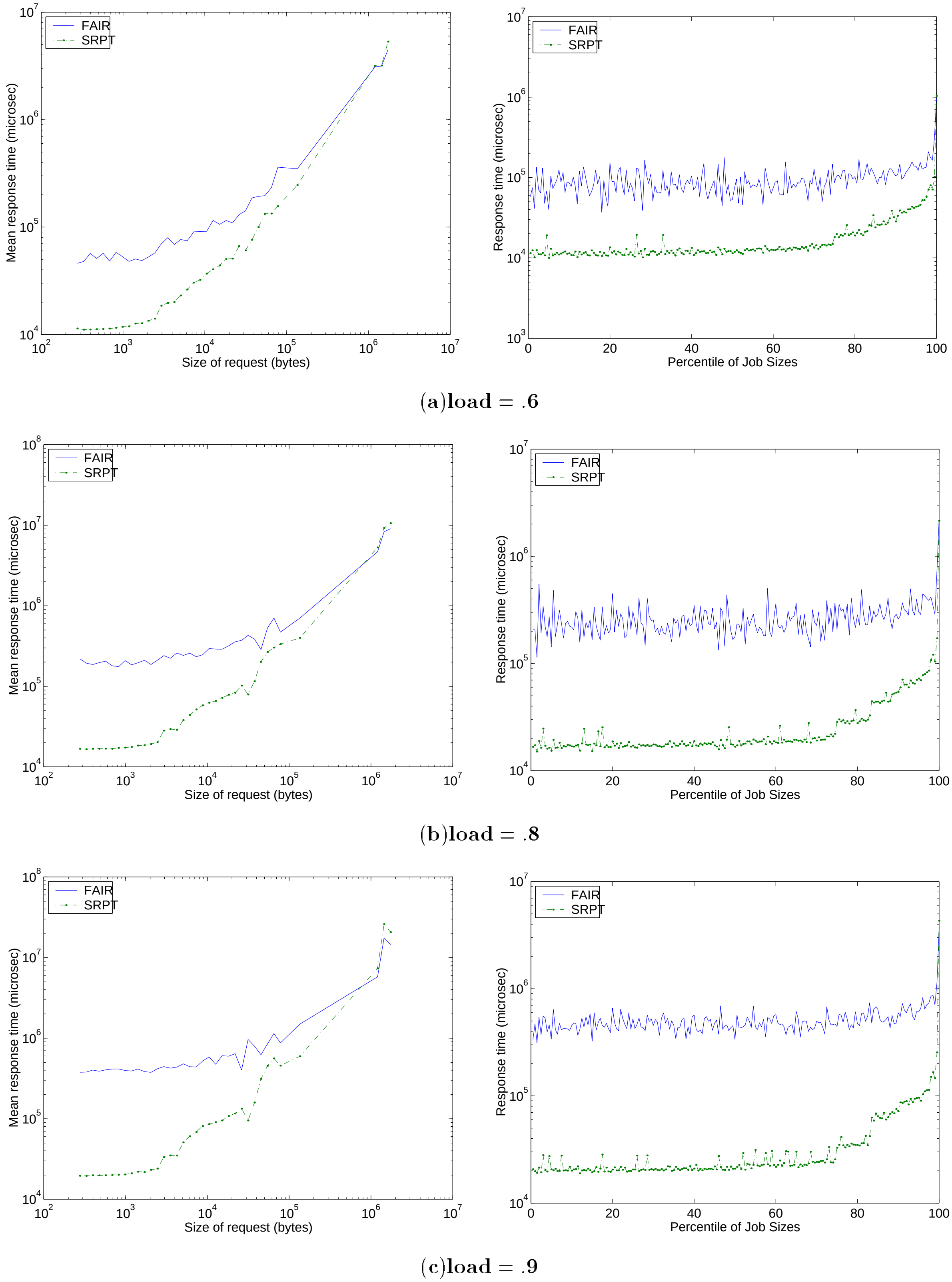
Figure 4: *Mean slowdown under SRPT scheduling versus traditional FAIR scheduling as a function of system load, under trace-based workload.*

For lower loads, the difference in mean response time between SRPT and FAIR scheduling decreases, and the unfairness to big requests becomes practically nonexistent. For higher loads, the difference in mean response time between SRPT and FAIR scheduling becomes greater, and the unfairness to big requests also increases. Even here though, it is only the top half of one percent of all requests which have worse performance under SRPT, as compared with FAIR scheduling.

Even for the highest load tested (.95), there are only 50 requests (out of the 90,000 requests) which complete later under SRPT as compared with FAIR. These jobs are so large however, that the effect on their slowdown is negligible.

The most dramatic improvements of SRPT are in the area of variance reduction. Figure 6 shows the variance in response time for each request size as a function of the percentile of the request size distribution. This figure shows the case of 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 close to an order of magnitude for most file sizes. The improvement in mean variance overall is a factor of about 8.

It is interesting to observe that the SRPT variance results curve is relatively smooth, except for a few odd spikes. The spikes represent occasional packet loss. If an initial packet is lost, there is a 3 second delay (because RTT has not yet been adjusted). This affects the variance in SRPT. It also affects the variance in PS,



(a)load = .6

(b)load = .8

(c)load = .9

Figure 5: *Mean response time as a function of request size under trace-based workload, shown for a range of system loads. 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.*

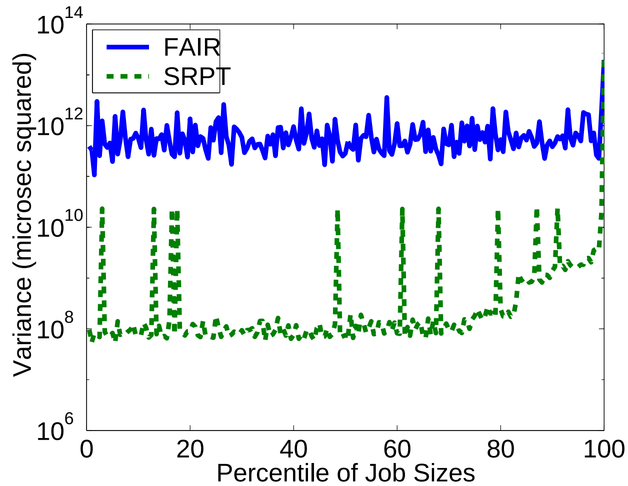


Figure 6: *Variance in response time as a function of the percentile of the request size distribution for SRPT as compared with FAIR scheduling, under trace-based workload with load* = 0.8.

however that is not noticeable in the graph because the variance in PS is already so high (note the log scale).

6 Explanation of Results

The results in the previous section may appear surprising. In this section we offer both a *theoretical* and an *implementation-level* explanation for the previous results.

6.1 Theoretical Explanation of Results

It is well-known that the SRPT scheduling policy always produces the minimum mean response time, for any sequence of requests. However, it has also 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 there is a finite maximum request size, which means that the moments are all finite, but still quite high.

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

Request sizes are well-known to follow a heavy-tailed distribution [9, 11]. Thus Web workload generators like `Surge` specifically use a heavy-tailed distribution in their model. Our traces also have strong heavy-tailed properties. (In our trace the largest $< 3\%$ of the requests make up $> 50\%$ of the total load.)

The important property of heavy-tailed distribution is the heavy-tailed property. 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 for a heavy-tailed workload. The reason is that this big request only competes against 50% of the load under SRPT (the remaining 50% of the load is made up of requests in the top 1%-tile of the request size distribution) whereas it competes against 100% of the 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). To understand this, we refer the reader to [21].

6.2 Implementation-level Explanation of Results

Section 6.1 concentrated primarily on why the SRPT-based policy performed so well. Another perspective is to ask why the FAIR policy performed so poorly. To see this, consider more carefully Figure 1 which shows flow of control in standard Linux. Observe that all socket buffers drain into the same single priority queue. This queue may grow long (though it is still bounded in length by a Linux parameter). Now consider the effect on a new short request. Since every request has to wait in the priority queue, which may be long, the short request typically incurs a cost of close to 120 ms just for waiting in this queue (assuming high load). This is a very high startup penalty, considering that the service time for a short request should really only be about 10-20 ms. Our SRPT-based implementation allows short requests to wait in their own separate priority queue which has a very low load and therefore is much shorter. This explains why the response time for short requests improves by close to an order of magnitude under SRPT, as compared with FAIR scheduling[2].

7 How to get SRPT-like improvements without using SRPT

The results of the previous section were good, but required a full implementation of the SRPT algorithm. In this section we explore a "quick fix" to Linux. We use only 3 priority bands. All SYN ACKS and all small

[2]Observe that the lovely mechanism of [13] which maintains a separate queue for each connection all the way down to the datalink level will likely fix this problem in Linux, if applied at the server end.

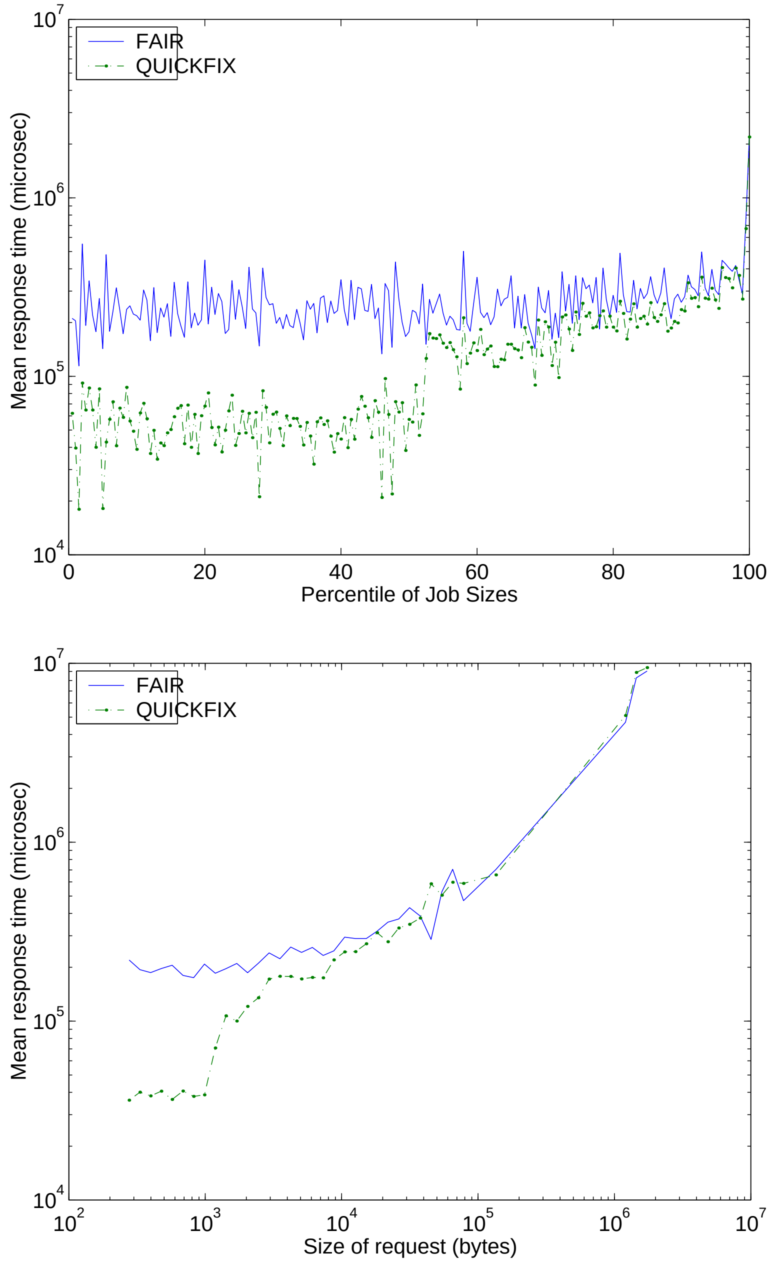


Figure 7: *Mean response time as a function of file size under quick-fix scheduling versus traditional FAIR scheduling, under trace-based workload, with load* 0.8.

requests go to band 0. All small requests go to band 1 and all large requests to band 2. We define the cutoff between "small" and "large" such that 50% of the requests are small and 50% are large (note, this is not the same thing as equalizing load). See Section 3.3.1 on rules of thumb for choosing cutoffs. The cutoff falls at 1K.

We find that this "quick fix" alone is quite powerful. Figure 7 shows the mean response time as a function of file size in the case of system load 0.8. Compare this figure with the results using the full SRPT implementation, shown in Figure 5(b). The "quick fix" benefits the smallest 50% of requests by a factor of 5, while not harming the large requests at all. This results in a factor of 2.5 improvement in mean response time and a factor of 5 improvement in mean slowdown. Note that the quick fix only helps 50% of the requests as compared to 99.5% which were helped in the SRPT implementation. Nonetheless, the quick fix still presents significant improvement over traditional FAIR scheduling.

8 Conclusion

This paper presents a kernel-level implementation of SRPT scheduling of connections in a Web server, and demonstrates that this implementation can significantly improve performance at the Web server.

Mean response time at the server can improve by 200% under low loads and as much as 800% under high loads. Mean slowdown can improve by as much as 1600% under high loads. Variance in response time can improve by orders of magnitude. All the while, the SRPT-based implementation hardly penalizes large requests (by "large" requests we mean those that comprise the top 0.5% of the request size distribution). Furthermore these gains are achieved under no loss in byte throughput or request throughput.

This paper also takes a closer look at the Linux kernel from a queueing perspective. Quick fixes to the Linux kernel are proposed which have the effect of limiting the queueing in the kernel, and which benefit many requests without hurting any.

9 Limitations of this paper and Future work

The following are some limitations of this paper and plans for future work.

Obvious extensions to this work include extending it to other operating systems, other Web servers, and other workload tests. We do not believe that our results will change for different Web servers or operating systems, but these must be verified.

Our current setup is limited in that we have zero propagation delay. Adding propagation delay may increase the scope of the problem dramatically. For example, once propagation delay is introduced, it is no longer even clear what we mean by the "size" of a request. Should a request for a small file from a client who is far away be considered small or large?

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 better predicting the size of dynamic requests, or deducing them over time. We expect that the effect of SRPT scheduling might be even more dramatic for cgi-scripts because such requests have much longer running times.

In this paper we have concentrated on reductions in mean response time, mean slowdown, and variance in response time. Another area worth studying is the effect of SRPT-based scheduling on improving the *responsiveness* of a Web server. Web requests are often comprised of text, icons, and images. A client can not make progress until all the text and icons are loaded, but he does not require all the images to be loaded. SRPT-based scheduling would give priority to text and icons (which represent small requests), reducing the time for the Web server to retrieve text and icons by a factor of about 10.

Our current setup considers network bandwidth to be the bottleneck resource and does 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.

Lastly, at present we only reduce mean delay at the *server*. A future goal is to use SRPT connection-scheduling at proxies. Our long-term goal is to extend our SRPT connection-scheduling technology to routers and switches in the Internet. In this way, the benefit of SRPT scheduling is not just limited to Web servers and other application end-nodes, but rather can help reduce congestion throughout the Internet.

10 Acknowledgements

We would like to thank Mark Crovella and Srini Seshan for many productive discussions on the topic of scheduling in Web servers and Linux flow control. Greg Kesden and Jan Harkes also provided us with helpful information about Linux internals. We would also like to thank Alexey Kuznetsov, Steven Ives and Tim Canfield for helping us with the initial Linux Diffserv experimentation. Lastly, we thank our many readers who gave us feedback on this paper including Ion Stoica and M. Satyanarayanan and Srini Seshan.

References

[1] J. Almeida, M. Dabu, A. Manikutty, and P. Cao. Providing differentiated quality-of-service in Web hosting services. In *Proceedings of the First Workshop on Internet Server Performance*, June 1998.

[2] Werner Almesberger. Linux network traffic control — implementation overview. Available at http://lrcwww.epfl.ch/linux-diffserv/.

[3] Werner Almesberger, Jamal Hadi, and Alexey Kuznetsov. Differentiated services on linux. Available at http://lrcwww.epfl.ch/linux-diffserv/.

[4] Baily, Foster, Hoang, Jette, Klingner, Kramer, Macaluso, Messina, Nielsen, Reed, Rudolph, Smith, Tomkins, Towns, and Vildibill. Valuation of ultra-scale computing systems. White Paper, 1999.

[5] Hari Balakrishnan, Venkata Padmanabhan, and Randy Katz. The effects of asymmetry on TCP performance. *ACM Mobile Networks and Applications*, 4(3), 1999.

[6] Paul Barford and Mark E. Crovella. Generating representative Web workloads for network and server performance evaluation. In *Proceedings of SIGMETRICS '98*, pages 151–160, July 1998.

[7] Michael Bender, Soumen Chakrabarti, and S. Muthukrishnan. Flow and stretch metrics for scheduling continuous job streams. In *Proceedings of the 9th Annual ACM-SIAM Symposium on Discrete Algorithms*, 1998.

[8] Mark E. Crovella and Azer Bestavros. Self-similarity in World Wide Web traffic: Evidence and possible causes. In *Proceedings of the 1996 ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems*, pages 160–169, May 1996.

[9] Mark E. Crovella and Azer Bestavros. Self-similarity in World Wide Web traffic: Evidence and possible causes. *IEEE/ACM Transactions on Networking*, 5(6):835–846, December 1997.

[10] Mark E. Crovella, Robert Frangioso, and Mor Harchol-Balter. Connection scheduling in web servers. In *USENIX Symposium on Internet Technologies and Systems*, October 1999.

[11] Mark E. Crovella, Murad S. Taqqu, and Azer Bestavros. Heavy-tailed probability distributions in the World Wide Web. In *A Practical Guide To Heavy Tails*, pages 3–26. Chapman & Hall, New York, 1998.

[12] Allen B. Downey. A parallel workload model and its implications for processor allocation. In *Proceedings of High Performance Distributed Computing*, pages 112–123, August 1997.

[13] Peter Druschel and Gaurav Banga. Lazy receiver processing (LRP): A network subsystem architecture for server systems. In *Proceedings of OSDI '96*, October 1996.

[14] Abhijith Halikhedkar, Ajay Uggirala, and Dilip Kumar Tammana. Implemenation of differentiated services in linux (diffspec). Available at http://www.rsl.ukans.edu/ dilip/845/FAGASAP.html.

[15] Internet Town Hall. The internet traffic archives. Available at `http://town.hall.org/Archives/pub/ITA/`.

[16] M. Harchol-Balter and A. Downey. Exploiting process lifetime distributions for dynamic load balancing. *ACM Transactions on Computer Systems*, 15(3), 1997.

[17] Mor Harchol-Balter. Task assignment with unknown duration. In *Proceedings of ICDCS '00*, April 2000.

[18] Gordon Irlam. Unix file size survey - 1993. Available at `http://www.base.com/gordoni/ufs93.html`, September 1994.

[19] W. E. Leland and T. J. Ott. Load-balancing heuristics and process behavior. In *Proceedings of Performance and ACM Sigmetrics*, pages 54–69, 1986.

[20] S. Manley and M. Seltzer. Web facts and fantasy. In *Proceedings of the 1997 USITS*, 1997.

[21] Authors omitted for purpose of double-blind reviewing. Analysis of SRPT scheduling: Investigating unfairness. In *To appear in Proceedings of* Sigmetrics '01.

[22] Authors omitted for purpose of double-blind reviewing. Implementation of SRPT scheduling in web servers. Technical Report XXX-CS-00-170, 2000.

[23] Vivek S. Pai, Peter Druschel, and W. Zwaenepoel. Flash: An efficient and portable web server. In *Proceedings of USENIX 1999*, June 1999.

[24] David L. Peterson and David B. Adams. Fractal patterns in DASD I/O traffic. In *CMG Proceedings*, December 1996.

[25] Saravanan Radhakrishnan. Linux – advanced networking overview version 1. Available at http://qos.ittc.ukans.edu/howto/.

[26] J. Roberts and L. Massoulie. Bandwidth sharing and admission control for elastic traffic. In *ITC Specialist Seminar*, 1998.

[27] Linus E. Schrage and Louis W. Miller. The queue M/G/1 with the shortest remaining processing time discipline. *Operations Research*, 14:670–684, 1966.

[28] Anees Shaikh, Jennifer Rexford, and Kang G. Shin. Load-sensitive routing of long-lived ip flows. In *Proceedings of SIGCOMM*, September 1999.

11 Appendix

The following are results for the same experiments as shown in the paper, except that this time with use the `Surge`-modified workloads rather than the trace-driven workloads, as explained in Section 4.2.

The Web workload generator we use is an adaptation of the popular `Surge` Web workload generator [6]. `Surge` generates HTTP requests that follow the size distribution of empirically-measured request sizes, namely a heavy-tailed distribution with α-parameter 1.1, where most files have size less than 5K bytes, but mean file 11108 bytes. In addition to HTTP request sizes, `Surge`'s stream of HTTP requests also adheres to measurements of the sizes of files stored on the server; the relative popularity of files on the server; the temporal locality present in the request stream; and the timing of request arrivals at the server.

We have modified `Surge` in several ways. First of all, the `Surge` workload generator uses a *closed* queueing model. We have modified the code to create an *open* model. This allows us more careful control over the system load, while still adhering to the statistical characteristics of the `Surge` requests. We use 1000 different file sizes at the Web server, ranging from 76 Bytes to 2 MB, with mean 13727 Bytes.

Second, the `Surge` system provides an overly-optimistic view of starvation, since it only records response times for those requests which have completed. Thus if there is a large request which never completed (is still sitting in the queue) during the experiment under SRPT, that request would not be recorded by `Surge`. This limitation yields a lower mean response time for large requests than is actually the case. Since starvation is a central theme in this paper, we have taken extra care in this area. We have modified `Surge` so that the response times of these large requests which remain in the queue are included in the mean calculation. ur modification to `Surge` results in a significant increase in mean response time and starvation. All our plots depict these higher mean and starvation numbers.

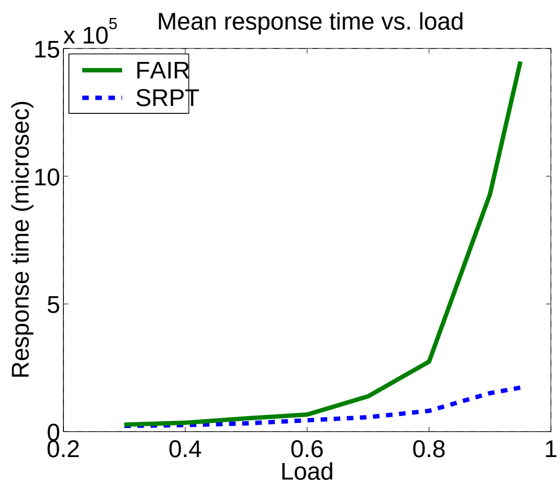
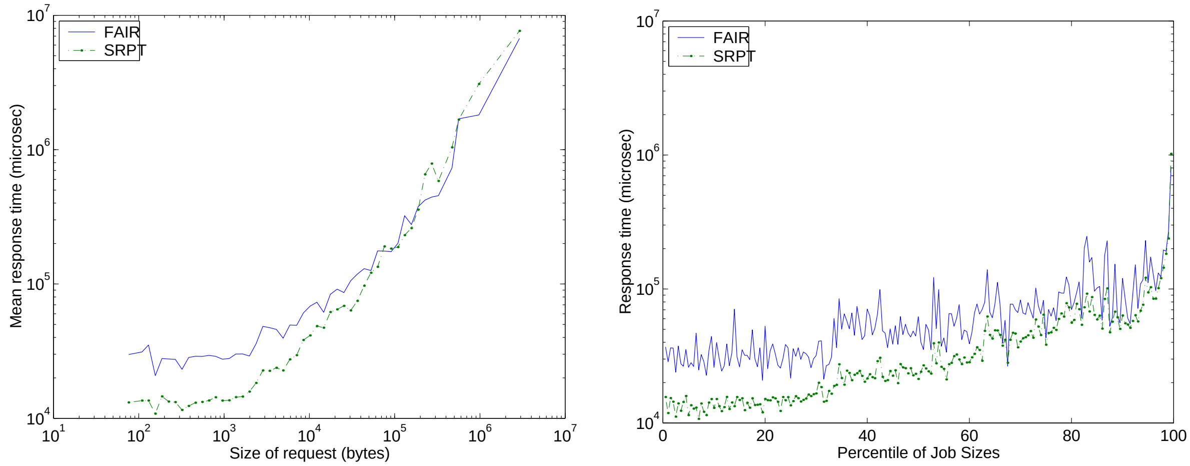
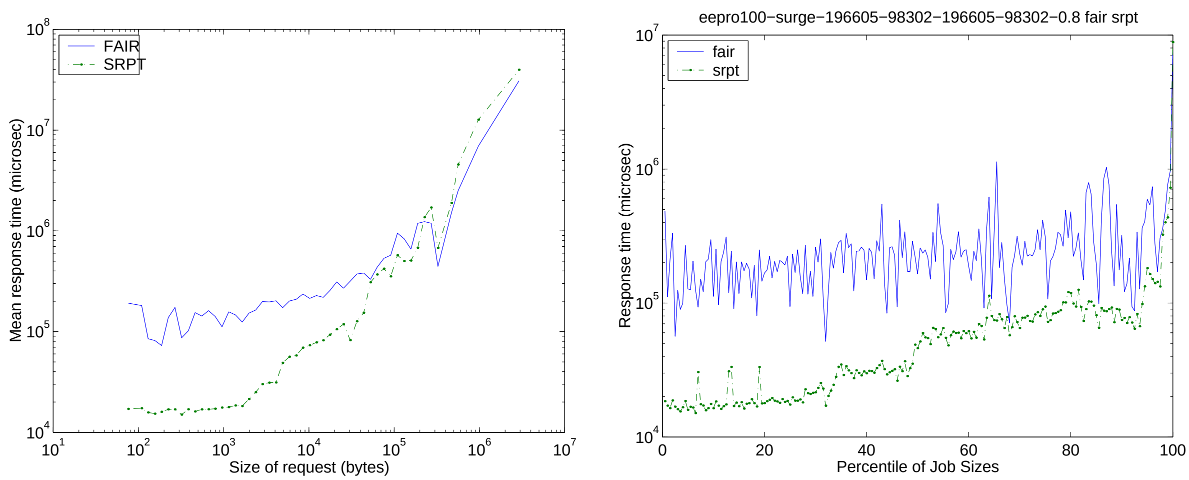


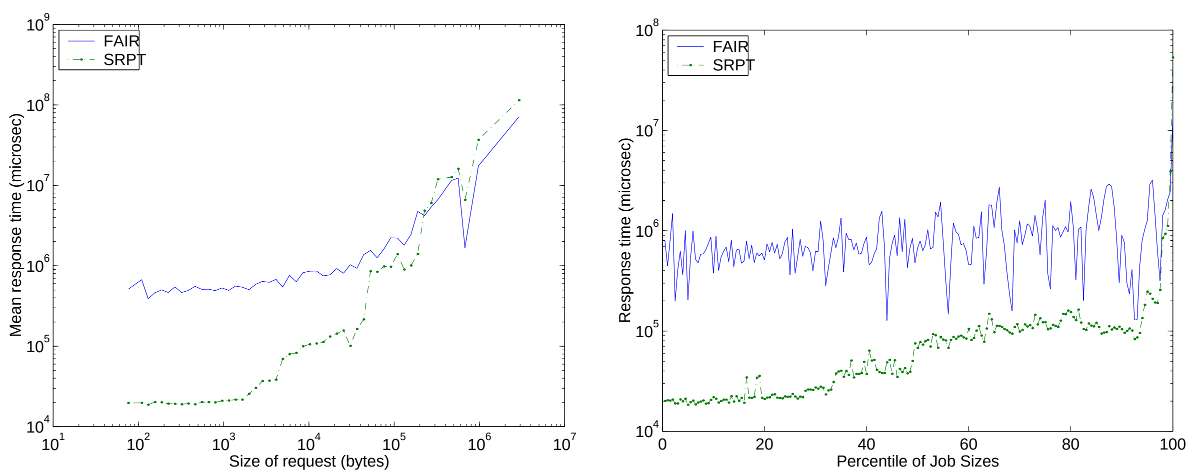
Figure 8: *Mean response time under SRPT scheduling versus traditional FAIR scheduling as a function of system load, under* `Surge`*-modified workload.*



(a)load = .6



(b)load = .8



load = .9

Figure 9: *Mean response time as a function of request size under* `Surge`*-modified workload, shown for a range of system loads. 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.*

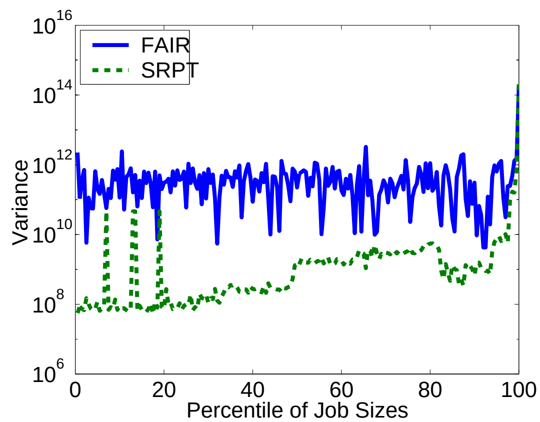


Figure 10: *Variance in response time as a function of the percentile of the request size distribution for SRPT as compared with FAIR scheduling, under* `Surge`*-modified workload with load* = 0.8.

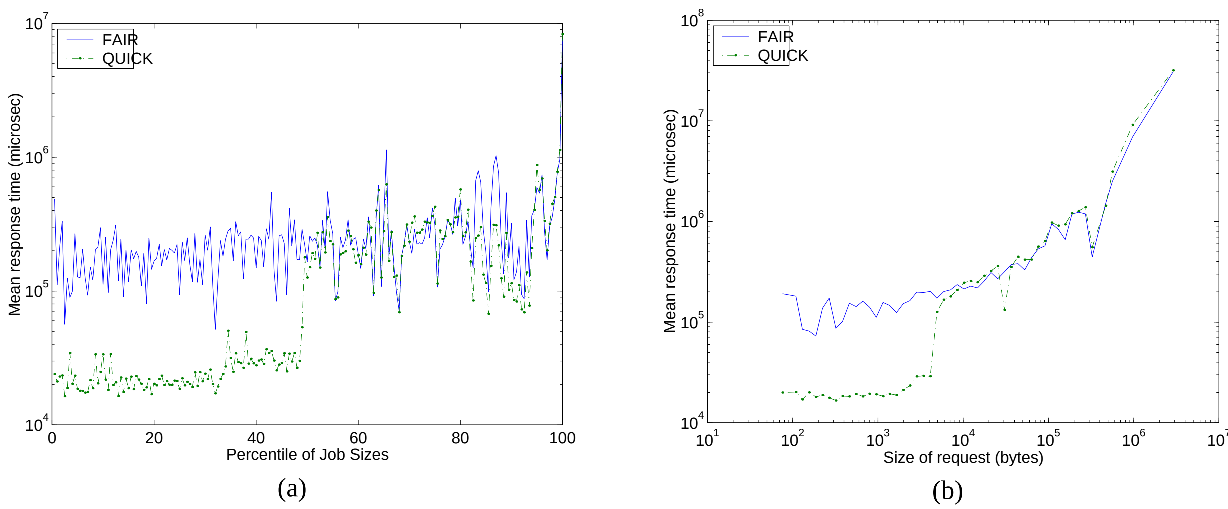


Figure 11: *Mean response time shown (a) as a function of request size and (b) as a function of percentile of request size, for quick-fix scheduling versus traditional FAIR scheduling, under* `Surge`*-modified workload, with load* 0.8.