Evaluation of Task Assignment Policies for Supercomputing Servers: The Case for Load Unbalancing and Fairness

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Abstract

While the MPP is still the most common architecture in supercomputer centers today, a simpler and cheaper machine configuration is growing increasingly common. This alternative setup may be described simply as a *collection of multiprocessors* or a *distributed server system*. This collection of multiprocessors is fed by a single common stream of jobs, where each job is dispatched to exactly *one* of the multiprocessor machines for processing.

The biggest question which arises in such distributed server systems is what is a good policy for assigning jobs to host machines. Many task assignment policies have been proposed, but not systematically evaluated under supercomputing workloads. In this paper we start by comparing existing task assignment policies using a trace-driven simulation under supercomputing workloads. We use analysis to validate our results and to provide intuition. We find that while the performance of supercomputing servers varies widely with the task assignment policy, none of the above policies perform as well as we would like.

We observe that all task assignment policies proposed thus far aim to balance load among the hosts. We propose a policy which purposely *unbalances* load among the hosts, yet, counter-to-intuition, is also *fair* in that it achieves the same expected slowdown for all jobs – thus no jobs are biased against. We evaluate this policy again using both trace-driven simulation and analysis. We find that the performance of the load unbalancing policy is significantly better than the best of those policies which balance load.

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1 Introduction

This paper considers an increasingly popular machine configuration in supercomputer centers today, and addresses how best to schedule jobs within such a configuration.

1.1 Architectural model

The setup may be described simply as a *collection of multiprocessors* or a *distributed server system*. This collection of multiprocessors is fed by a single common stream of batch jobs, where each job is dispatched to exactly *one* of the multiprocessor machines for processing. Observe that we specifically do *not* use the word "cluster" because the word "cluster" in supercomputing today includes the situation where a single job might span more than one of these multiprocessors.

Figure 1 shows a very typical example of a distributed server system consisting of a dispatcher unit and 4 identical host machines. Each host machine consists of 8 processors and one shared memory. In practice the "dispatcher unit" may not exist and the clients themselves may decide which host machine they want to run their job on. Jobs which have been dispatched to a particular host are run on the host in FCFS (first-come-first-served) order. Typically, in the case of batch jobs, *exactly one* job at a time occupies each host machine (the job is designed to run on 8 processors), although it is sometimes possible to run a very small number of jobs simultaneously on a single host machine, if the total memory of the jobs fits within the host machine's memory space. The jobs are each *run-to-completion* (i.e., no preemption, no time-sharing). We will assume the above model throughout this paper, see Section 2.2.

Run-to-completion is the common mode of operation in supercomputing environments for several reasons. First, the memory requirements of jobs tend to be huge, making it very expensive to swap out a job's memory [11]. Thus timesharing between jobs only makes sense if all the jobs being timeshared fit within the memory of the host, which is very unlikely. Also, many operating systems that enable timesharing for single-processor jobs, do not facilitate preemption among several processors in a coordinated fashion. Furthermore, preempting jobs can cause problems if jobs access files from a distributed file system, since the open files of a job can change while the job is preempted.

While the distributed server configuration described above is less flexible than an MPP, system administrators we spoke with at supercomputing centers favor distributed servers for their ease of administration, ease of scheduling, scalability, and price [6]. Also, the system administrators felt that distributed servers achieve better utilization of resources and make users happier since they are better able to predict when their job will get to run.

Examples of distributed server systems that fit the above description are the Xolas distributed server at the MIT Lab for Computer Science (LCS), which consists of eight 8-processor Ultra HPC 5000 SMPs [17], the Pleiades Alpha Cluster also at LCS, which consists of seven 4-processor Alpha 21164 machines [16], the Cray J90 distributed server at NASA Ames Research Lab, which consists of four 8-processor Cray J90 machines, the Cray J90 distributed server at the Pittsburgh Supercomputing Center (PSC), which consists of two 8-processor Cray J90 machines [1], and the Cray C90 distributed server at NASA Ames Research Lab, which consists of two 16-processor Cray C90 machines [2].

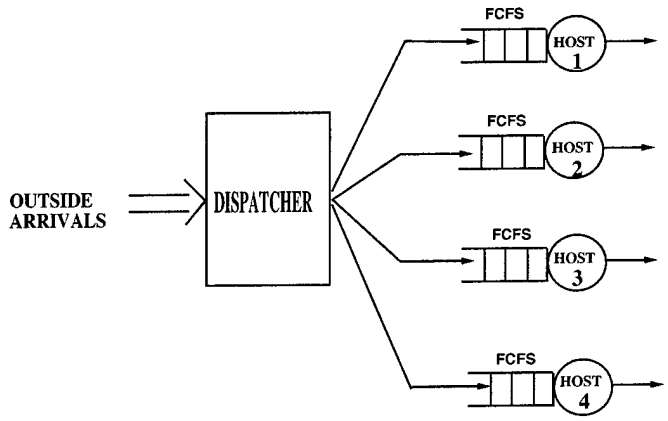

Figure 1: *Illustration of a distributed server with 4 host machines, each of which is a multiprocessor.*

1.2 The Task Assignment Problem

The main question in distributed servers such as those described above is "What is a good task assignment policy." A *task assignment policy* is a rule for assigning jobs (tasks) to host machines. Designing a distributed server system often boils down to choosing the "best" task assignment policy for the given model and user requirements. The question of which task assignment policy is "best" is an age-old question which still remains open for many models.

Our main performance goal, in choosing a task assignment policy, is to minimize *mean response time* and more importantly *mean slowdown*. A job's slowdown is its response time divided by its service requirement. (Response time denotes the time from when the job arrives at the system until the job completes service. Service requirement is just the CPU requirement – in our case this is the response time minus the queueing time.) All means are per-job averages. Mean slowdown is important because it is desirable that a job's response time be proportional to its processing requirement [9, 4, 14]. Users are likely to anticipate short delays for short jobs, and are likely to tolerate long delays for longer jobs. For lack of space, we have chosen to only show mean slowdown in the graphs in this paper, although we will also comment on mean response time. A second performance goal is *variance in slowdown*. The lower the variance, the more predictable the slowdown. A third performance goal is *fairness*. We adopt the following definition of fairness: All jobs, long or short, should experience the same expected slowdown. In particular, long jobs shouldn't be penalized – slowed down by a greater factor than are short jobs.[1]

Observe that for the architectural model we consider in this paper, memory usage is not an issue with respect to scheduling. Recall that in the above described distributed server system, hosts are identical and each job has exclusive access to a host machine and its memory. Thus a job's memory requirement is not a factor in scheduling. However CPU usage is very much an issue in scheduling.

Consider some task assignment policies commonly proposed for distributed server systems: In the `Random` task assignment policy, an incoming job is sent to Host i with probability $1/h$, where h is the number of hosts. This policy equalizes the expected number of jobs at each host. In `Round-Robin` task assignment, jobs are assigned to hosts in a cyclical fashion with the ith job being assigned to Host $i \bmod h$. This policy also equalizes the expected number of jobs at each host, and has slightly less variability

[1]For example, Processor-Sharing (which requires infinitely-many preemptions) is ultimately fair in that every job experiences the same expected slowdown.

in the interarrival times at each host than does Random. In Shortest-Queue task assignment, an incoming job is immediately dispatched to the host with the fewest number of jobs. This policy tries to equalize the instantaneous number of jobs at each host, rather than just the expected number of jobs. The Least-Work-Left policy sends each job to the host with the currently least remaining work. Observe that Least-Work-Left comes closest to obtaining instantaneous load balance. The Central-Queue policy holds all jobs at the dispatcher in a FCFS queue, and only when a host is free does the host request the next job. Lastly, the SITA-E policy, suggested in [13], does duration-based assignment, where "short" jobs are assigned to Host 1, "medium-length" jobs are assigned to Host 2, "long" jobs to Host 3, etc., where the duration cutoffs are chosen so as to equalize load (SITA-E stands for Size Interval Task Assignment with Equal Load). This policy requires knowing the *approximate duration* of a job. All the above policies aim to balance the load among the server hosts.

What task assignment policy is generally used in practice? This is a difficult question to answer. Having studied Web pages and spoken to several system administrators, we conclude that task assignment policies vary widely, are not well understood, and often rely on adhoc parameters. The Web pages are very vague on this issue and are often contradicted by users of these systems [7]. The schedulers used are Load-Leveler, LSF, PBS, or NQS. These schedulers typically only support run-to-completion (no preemption) [18].

In several distributed servers we looked at, the users submit an upper bound on the processing requirement of their job. In some systems task assignment is determined by the user. The jobs at each machine are run-to-completion, one-at-a-time in FCFS order. In making his decision, the user can estimate the queueing time on each of the host machines by totalling the estimated run times of the jobs which have been assigned to each machine. The user chooses to send his job to the machine with lowest queueing time. This is the Least-Work-Left policy. Other distributed servers use more of a SITA-E policy, where different host machines have different duration limitations: up to 2 hours, up to 4 hours, up to 8 hours, or unlimited. In yet other distributed server systems, the scheduling policies are closer to Round-Robin.

1.3 Relevant Previous Work

The problem of task assignment in a model like ours has been studied extensively, but many basic questions remain open. See [13] for a long history of this problem. Much of the previous literature has only dealt with Exponentially-distributed job service requirements. Under this model, it has been shown that the Least-Work-Left policy is the best. A recent paper, [13], has analyzed the above policies assuming the job service requirements are *i.i.d.* distributed according to a heavy-tailed Pareto distribution. Under that assumption SITA-E was shown to be the best of the above policies, by far. Several papers make the point that the distribution of the job service requirement has a huge impact on the relative performance of scheduling policies [13, 9, 11]. No paper we know of has compared the above task assignment policies on supercomputing trace data (real job service requirements).

The idea of purposely unbalancing load has been suggested previously in [8], [5], and [12] under very different contexts from our paper. In [8] a distributed system with *preemptible* tasks is considered. It is shown that in the preemptible model, mean response time is minimized by *balancing* load, however mean slowdown is minimized by *un*balancing load. In [5], *real-time scheduling* is considered where jobs have firm *deadlines*. In this context, the authors propose "load profiling," which "distributes load in such a way that the probability of satisfying the utilization requirements of incoming jobs is maximized." Our paper also differs from [12] which concentrates on the problem of task assignment with *unknown* service times. [12] is limited to analysis

only, and restricted to the Pareto distribution only.

The notion of *fairness* is also mentioned often, but with a very different meaning from that in this paper [19, 15, 3].

1.4 Paper contributions

In this paper we propose to do two things: First, we will compare all of the task assignment policies listed in Section 1.2 in a trace-driven simulation environment using job traces from supercomputing servers which fit the above model. In simulation we are able to study both mean and variance metrics. We also use analysis to validate some of the simulation results, and to provide a lot of intuition. We find that there are big differences between the performance of the task assignment policies. In this paper, we concentrate on the case of 2 host machines. We find that `Random` and `Least-Work-Left` differ by a factor of 2 - 10 (depending on load) with respect to mean slowdown, and by a factor of 30 with respect to variance in slowdown. `Random` and `SITA-E` differ by a factor of 6 - 10 with respect to mean slowdown and by several orders of magnitude with respect to variance in slowdown. Increasing the number of host machines above 2 creates even more dramatic differences. Nevertheless, none of these task assignment policies perform as well as we would like.

This leads us to the question of whether we are looking in the right search space for task assignment policies. We observe that all policies proposed thus far aim to balance load among the hosts. We propose a new policy which purposely *unbalances* load among the hosts. Counter-to-intuition, we show that this policy is also *fair* in that it achieves the same expected slowdown for all jobs – thus no jobs are biased against. We show surprisingly that the optimal degree of load unbalancing seems remarkably similar across many different workloads. We derive a rule of thumb for the appropriate degree of unbalancing. We evaluate our load unbalancing policy again using both trace-driven simulation and analysis. The performance of the load unbalancing policy improves upon the best of those policies which balance load by more than an order of magnitude with respect to mean slowdown and variance in slowdown.

We feel that the above results are dramatic enough that they should affect the direction we take in developing task assignment policies. We elaborate on this in the conclusion.

2 Experimental Setup

This section describes the setup of our simulator and the trace data.

2.1 Collection of job traces

The first step in setting up our simulation was collecting trace data. In collecting job data, we sought data from systems which most closely matched the architectural model in our paper. We obtained traces from the PSC for the J90 and the C90 machines. Recall from Section 1.1 that these machines are commonly configured into distributed server systems. Jobs on these machines are run-to-completion (no stopping/preempting). The jobs on these machines were submitted under the category of "batch" jobs.

The figures throughout this paper will be based on the C90 trace data. All the results for the J90 trace data are virtually identical and are provided in Appendix B. For the purpose of comparison, we also consider

a trace of jobs which comes from a 512-node IBM-SP2 at Cornell Theory Center (CTC). Although this trace did *not* come from the distributed server configuration, it is interesting in the context of this work since it reflects a common practice in supercomputing centers: unlike the J90 and C90 jobs, the jobs in the CTC trace had an upper bound on the run-time, since users are told jobs will be killed after 12 hours. We were surprised to find that although this upper bound leads to a considerably lower variance in the service requirements, the comparative performance of the task assignment policies under the CTC trace was very similar to those for the J90 and C90 traces. All the CTC trace results[2] are shown in Appendix C. Characteristics of all the jobs used in this paper are given in the following table.

System	Duration	Number of Jobs	Mean Service Requirement (sec)	Min (sec)	Max (sec)	Squared Coefficient of Variation
PSC C90	Jan – Dec 1997	54962	4562.6	1	2222749	43.16
PSC J90	Jan – Dec 1997	3582	9448.6	4	618532	10.02
CTC IBM-SP2	July 1996 – May 1997	5729	2903.6	1	43138	5.42

The CTC trace was obtained from Feitelson's Parallel Workloads Archive [10]. The data collected above will be made public at `http://www.cs.cmu.edu/~harchol/supercomputing.html`.

2.2 Simulation Setup

Our trace-driven simulation setup is very close to that of Section 1.1. We simulate a distributed server for batch jobs with h host machines. *Throughout most of this paper we assume* $h = 2$. Jobs are dispatched immediately upon arrival to one of the host machines according to the task assignment policy. Jobs have *exclusive access* to host machines, and jobs are run-to-completion.

Although the job *service requirements* are taken from a trace, the job arrival times were not available to us, so we assume a Poisson *arrival* process. [13] makes the point that whereas the distribution of the job service requirement critically influences the relative (comparative) performance of the task assignment policies, the arrival process does not have nearly as strong an effect on the relative performance, although it does affect the absolute numbers. [3]

When obtaining simulation measurements, we record only every 10th departure, starting with the 100th departure and take the mean. We repeat the experiment 25 times and take the mean of the results. This creates one data point on the plots.

3 Evaluation of Policies which Balance Load

This section describes the result of our simulation of task assignment policies which aim to balance load.

[2]To make the workload more suitable for our model we used only those CTC jobs that require 8 processors, although using all jobs does lead to similar results.

[3]Observe that even if the arrival times were available to us, they might not be useful if the original distributed server has not the same number of hosts that we are simulating. Also, we were particularly interested in studying the role of the system load in choosing a good task assignment policy. Using actual arrival times restricts us to the system load given by the job trace and it's not clear whether simple scaling of the interarrival times leads to realistic results. Furthermore, assuming Poisson arrivals allows us to abstract from irregularities like system downtimes.

3.1 The load balancing Task Assignment Policies

The task assignment policies we evaluate are Random, Least-Work-Left, and SITA-E, as described in Section 1.2. In [13] it was shown that the Least-Work-Left policy is equivalent to the Central-Queue policy for any sequence of job requests. Thus it suffices to only evaluate the former. We also evaluated the other policies mentioned e.g. Round-Robin, but their performance is not notable and we omitted it to avoid cluttering the graphs.

3.2 Results from Simulation

All the results in this section are trace-driven simulation results based on the C90 job data. The results for the J90 job data and other workloads are very similar and are shown in the Appendix. The plots only show system load up to 0.8 (because otherwise they become unreadable), however the discussion below spans all system loads under 1.

Figure 2(left) compares the performance of the policies which balance load (Random, Least-Work-Left, and SITA-E) in terms of their mean slowdown over a range of system loads. These results assume a 2-host distributed server system. Figure 2(right) makes the same comparison in terms of variance in slowdown. Observe that the slowdown under Random is higher than acceptable in any real system even for low loads and explodes for higher system loads. The slowdown under Random exceeds that of SITA-E by a factor of 10. The slowdowns under SITA-E and Least-Work-Left are quite similar for low loads, but for medium and high loads SITA-E outperforms Least-Work-Left by a factor of 3-4. The difference with respect to variance in slowdown is even more dramatic: Least-Work-Left improves upon the variance under Random by up to a factor of 10 and SITA-E in turn improves upon the variance under Least-Work-Left by up to a factor of 10.

The same comparisons with respect to mean response time (not shown here) are very similar. For system loads greater than 0.5, SITA-E outperforms Least-Work-Left by factors of 2-3, and Random is by far the worst policy. The difference with respect to variance in response time is not quite as dramatic as for variance in slowdown. While the variance under Random is again by up to a factor of ten higher than for SITA-E and Least-Work-Left, SITA-E improves the variance only by a factor of 1.5 upon that of Least-Work-Left.

Figure 3 again compares the performance of policies which balance load, except this time for a distributed server system with 4 hosts. Figure 3(right) makes the same comparison in terms of variance in slowdown. This figure shows that the slowdown and the variance in slowdown under both Least-Work-Left and SITA-E improves significantly when switching from 2 hosts to 4 hosts. The results for Random are the same as in the 2 host system. For low loads Least-Work-Left leads to lower slowdowns than SITA-E, but for system load 0.5 SITA-E improves upon Least-Work-Left by a factor of 2, and for high loads, SITA-E improves upon Least-Work-Left by a factor of 4. More dramatic are the results for the variance in slowdown: SITA-E outperforms the other two policies for all ranges of load, and SITA-E's variance in slowdown is 25 times lower than that of Least-Work-Left.

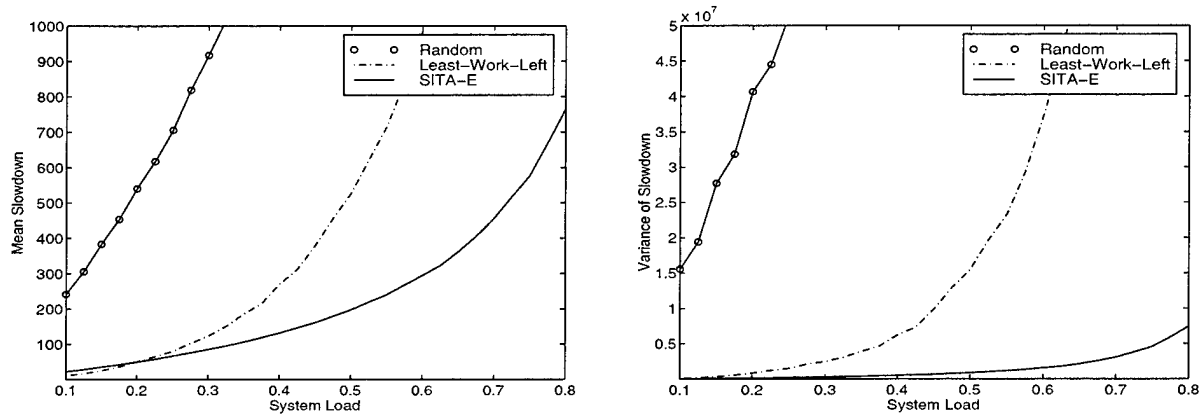

Figure 2: *Experimental comparison of task assignment policies which balance load for a system with 2 hosts in terms of: (left) mean slowdown and (right) variance in slowdown.*

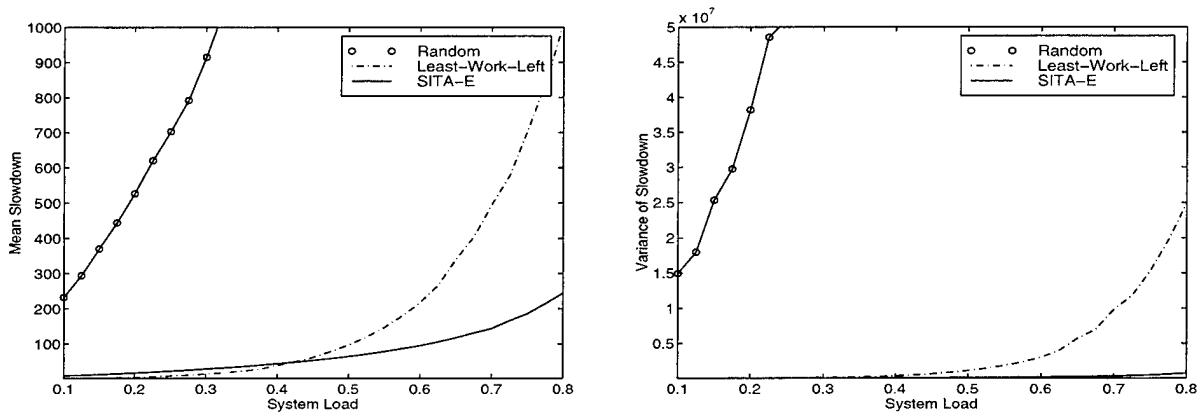

Figure 3: *Experimental comparison of task assignment policies which balance load for a system with 4 hosts.*

3.3 Results from Analysis

We also evaluated all of the above policies via analysis, based on the supercomputing workloads. Via analysis we were only able to evaluate the *mean* performance metrics. The results are shown in Appendix A, Figure 7. These are in very close agreement with the simulation results.

The analysis is beneficial because it explains *why* `SITA-E` is the best task assignment policy. For lack of space, we omit most of the analysis, providing the reader only with the resulting intuition.

The analysis of each task assignment policy makes use of the analysis of a single M/G/1/FCFS queue, which is given in Theorem 1 [Pollaczek-Kinchin] below:

Theorem 1 *Given an M/G/1 FCFS queue, where the arrival process has rate λ, X denotes the service time distribution, and ρ denotes the utilization ($\rho = \lambda \mathbf{E}\{X\}$). Let W be a job's waiting time in queue, S be its slowdown, and Q be the queue length on its arrival. Then,*

$$\mathbf{E}\{W\} = \frac{\lambda \mathbf{E}\{X^2\}}{2(1-\rho)} \qquad \textit{[The Pollaczek-Kinchin formula]}$$

$$\begin{aligned}\mathbf{E}\{S\} &= \mathbf{E}\{W/X\} = \mathbf{E}\{W\} \cdot \mathbf{E}\left\{X^{-1}\right\} \\ \mathbf{E}\{Q\} &= \lambda \mathbf{E}\{W\}\end{aligned}$$

Proof: The slowdown formulas follow from the fact that W and X are independent for a FCFS queue, and the queue size follows from Little's formula. A nice derivation of the waiting time formula is given in Kleinrock. ■

The above formula applies to just a single FCFS queue, *not* a distributed server. The formula says that *all* performance metrics for the FCFS queue (mean waiting time, mean slowdown, etc.) are dependent on the *variance* of the distribution of job service demands (this variance term is captured by the $\mathbf{E}\{X^2\}$ term above). Intuitively, reducing the variance in the distribution of job processing requirements is important for improving performance because it reduces the chance of a short job getting stuck behind a long job. For our job service demand distribution, the variance is very high ($C^2 = 43$). Thus it will turn out that a key element in the performance of task assignment policies is how well they are able to reduce this variance.

We now discuss the effect of high variability in job service times on a distributed server system under the various task assignment policies.

Random Assignment The `Random` policy simply performs Bernoulli splitting on the input stream. The result is that each host becomes an independent $M/G/1$ queue, with the same (very high) variance in job service demands as was present in the original stream of jobs. Thus performance is very bad. The load at the ith host, ρ_i, is equal to the system load, ρ. The arrival rate at the ith host is $1/h$-fraction of the total outside arrival rate. Theorem 1 applies directly, and all performance metrics are proportional to the second moment of G. Therefore, performance is poor if the second moment of the G is high.

Round Robin The `Round Robin` policy splits the incoming stream so each host sees an $E_h/G/1$ queue, where h is the number of hosts. This system has performance close to the `Random` policy since it still sees high variability in service times, which dominates performance.

Least-Work-Left The `Least-Work-Left` policy is equivalent to an M/G/h queue, for which there exist known approximations, [20],[22]:

$$\mathbf{E}\left\{Q_{M/G/h}\right\} \approx \mathbf{E}\left\{Q_{M/M/h}\right\} \cdot \frac{\mathbf{E}\{X^2\}}{\mathbf{E}\{X\}^2},$$

where X denotes the service time distribution, and Q denotes queue length. What's important to observe here is that the mean queue length, and therefore the mean waiting time and slowdown, are all still proportional to the second moment of the service time distribution, as was the case for `Random` and `Round-Robin`. The `Least-Work-Left` policy does however improve performance for another reason: This policy is optimal with respect to sending jobs to idle host machines when they exist.

SITA-E The `SITA-E` policy is the *only* policy which reduces the variance of job service times at the individual hosts. The reason is that Host 1 only sees small jobs and Host 2 only sees large jobs. For our

data, $\mathbf{E}\{X^2_{host1}\} = 4.5 \cdot 10^7$ and $\mathbf{E}\{X^2_{host2}\} = 6.5 \cdot 10^{10}$ and $\mathbf{E}\{X^2\} = 9.2 \cdot 10^8$. Thus we've reduced the variance of the job service time distribution at Host 1 a lot, and increased that at Host 2. The point though is that 98.7 % of jobs go to Host 1 under SITA-E and only 1.3 % of jobs go to Host 2 under SITA-E. Thus SITA-E is a great improvement over the other policies with respect to mean slowdown, mean response time, and variance of slowdown and response time.

4 Unbalancing Load Fairly

The previous policies all aimed to balance load. The `Least-Work-Left` policy in fact aimed to balance *instantaneous* load. However it is not clear *why* this is the best thing to do. We have no *proof* that load balancing minimizes mean slowdown or mean response time. In fact, a close look at the analysis shows that load *unbalancing* is desirable. In this section we show that load unbalancing is not only preferable with respect to all our performance metrics, but it is also desirable with respect to fairness. Recall, we adopt the following definition of fairness: All jobs, long or short, should experience the same expected slowdown. In particular, long jobs shouldn't be penalized – slowed down by a greater factor than are short jobs. Our goal in this section is to develop a fair task assignment policy with performance superior to that of all the other policies.

4.1 Definition of SITA-U-opt and SITA-U-fair

In searching for policies which don't balance load, we start with SITA-E, since in the previous section we saw that `SITA-E` was superior to all the other policies because of its variance-reduction properties. We define two new policies:

- `SITA-U-opt`: Size Interval Task Assignment with Unbalanced Load, where the service-requirement cutoff is chosen so as to minimize mean slowdown.
- `SITA-U-fair`: Size Interval Task Assignment with Unbalanced Load, where the service-requirement cutoff is chosen so as to maximize fairness.

In `SITA-U-fair`, the mean slowdown of *short* jobs is equal to the mean slowdown of *long* jobs.

The cutoff defining "long" and "short" for these policies was determined both analytically and experimentally using half of the trace data. Both methods yielded about the same result. Note that the search space for the optimal cutoff is limited by the fact that neither host machine is allowed to exceed a load of 1.

4.2 Simulation results for SITA-U-opt and SITA-U-fair

Figure 4 compares `SITA-E`, the best of the load balancing task assignment policies, with `SITA-U-opt` and `SITA-U-fair`.

What is most interesting about the above figures is that `SITA-U-fair` is only a slight bit worse than `SITA-U-opt`. Both `SITA-U-fair` and `SITA-U-opt` improve greatly upon the performance of `SITA-E`, (the best of the load balancing policies) both with respect to mean slowdown and especially with respect to

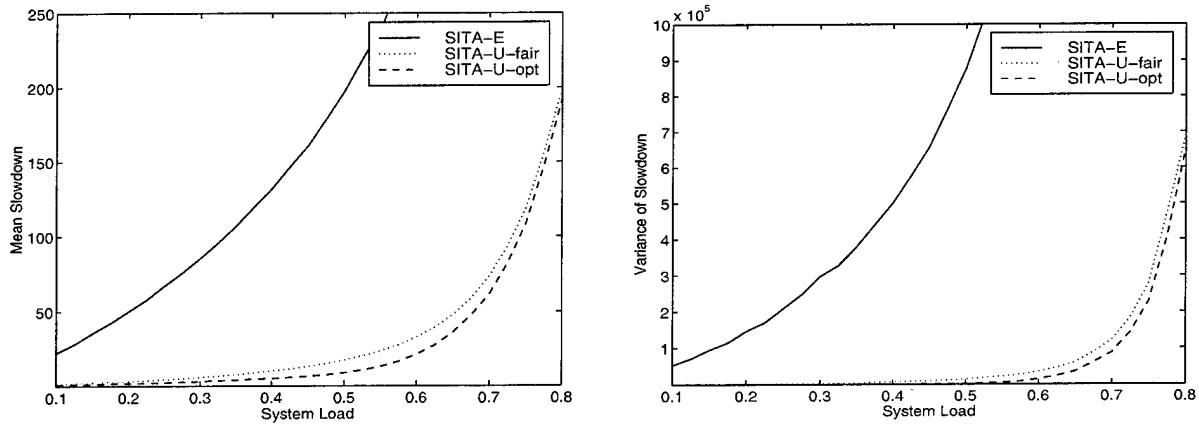

Figure 4: *Experimental Comparison of Mean Slowdown and Variance of Slowdown on* `SITA-E` *versus* `SITA-U-fair` *and* `SITA-U-opt` *as a Function of System Load.*

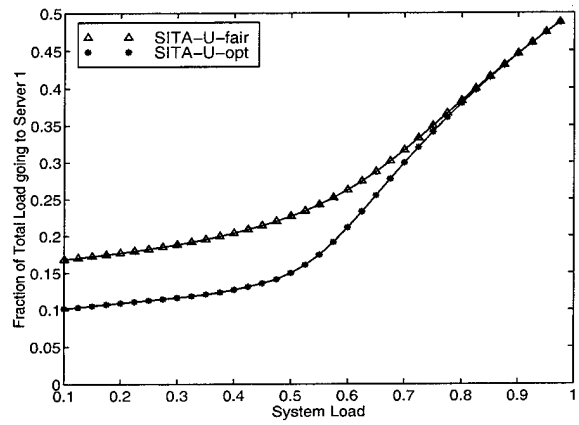

Figure 5: *Fraction of the total load which goes to Host 1 under SITA-U-opt and SITA-U-fair.*

variance in slowdown. In the range of load 0.5 - 0.8, the improvement of `SITA-U-fair` over `SITA-E` ranges from 4 - 10 with respect to mean slowdown, and from 10 - 100 with respect to variance in slowdown.

4.3 Analysis of SITA-U-opt and SITA-U-fair

Figure 8 in Appendix A shows the analytic comparison of mean slowdown for `SITA-E`, `SITA-U-opt`, and `SITA-U-fair`. These are in very close agreement with the simulation results.

Figure 5 shows the fraction of the total load which goes to Host 1 under `SITA-U-opt` and under `SITA-U-fair`. Observe that under `SITA-E` this fraction would always be 0.5.

Observe that for both `SITA-U-opt` and for `SITA-U-fair` we are underloading Host 1. Secondly observe that `SITA-U-opt` is not far from `SITA-U-fair`. In this section we explain these phenomena. We first explain why load unbalancing is desirable when optimizing overall mean slowdown of the system. We will later explain what happens when optimizing fairness.

The reason why it is desirable to operate at unbalanced loads is mostly due to the *heavy-tailed* nature of our workload. In our job service time distribution, half the total load is made up by only the biggest 1.3% of

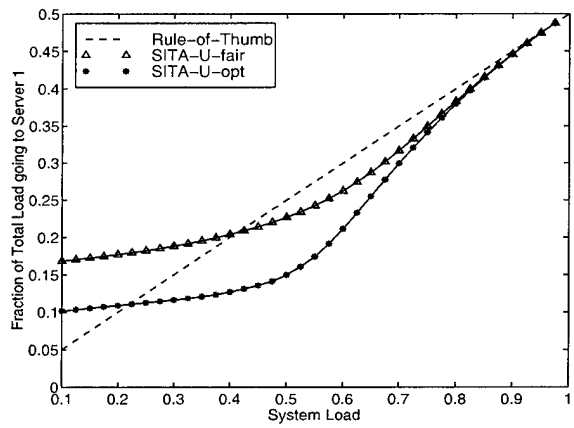

Figure 6: *Fraction of the total load which goes to Host 1 under SITA-U-opt and SITA-U-fair and our rule of thumb.*

all the jobs. This says that in `SITA-E` 98.7% of jobs go to Host 1 and only 1.3% of jobs go to Host 2. If we can reduce the load on Host 1 a little bit, by sending fewer jobs to Host 1, it will still be the case that most of the jobs go to Host 1, yet they are all running under a *reduced load.*

So load unbalancing optimizes mean slowdown, however it is not at all clear why load unbalancing also optimizes fairness. Under `SITA-U-fair`, the mean slowdown experienced by the short jobs is *equal* to the mean slowdown experienced by the long jobs. However it seems in fact that we're treating the long jobs unfairly because long jobs run on a host with extra load and extra variability in job durations.

So how can it possibly be fair to help short jobs so much? The answer is simply that the short jobs are short. Thus they need low response times to keep their slowdown low. Long jobs can afford a lot more waiting time, because they are better able to amortize the punishment over their long lifetimes. Note that this hold for all distributions. It is because our job service requirement distribution is so heavy-tailed that the long jobs are truly elephants (way longer than the shorts) and thus can afford more suffering.

4.4 A Rule of Thumb for Load Unbalancing

If load unbalancing is helpful, as seems to be the case, is there a rule of thumb for how much we should unbalance load?

Figure 6 gives a rough rule of thumb which says simply that if the system load is ρ, then the fraction of the load which is assigned to Host 1 should be $\rho/2$. For example, when the system load is 0.5, only $1/4$ of the total load should go to Host 1 and $3/4$ of the total load should go to Host 2. Contrast this with `SITA-E` which says that we should always send half the total load to each host.

We redid the simulations using out our rule-of-thumb cutoffs, rather than the optimal cutoffs, and the results were within 10%. We also tested out the rule-of-thumb when using the J90 data and when using the CTC data, and results were similar as well. Appendix Figures 10 and 12 show the rule-of-thumb fit for the J90 data and the CTC data respectively.

5 Conclusions and Implications

The contributions of this paper are detailed in Section 1.4, so we omit the usual summary and instead discuss some further implications of this work. There are a few interesting points raised by this work:

- Task assignment policies differ widely in their performance (by an order of magnitude or more)! The implication is that we should take the policy determination more seriously, rather than using whatever Load Leveler gives us as a default.
- The "best" task assignment policy depends on characteristics of the distribution of job processing requirements. Thus workload characterization is important. Although our model is nothing like an MPP, the intuitions we learned here with respect to workloads may help simplify the complex problem of scheduling in this more complicated architecture as well.
- What appear to just be "parameters" of the task assignment policy (e.g., duration cutoffs) can have a greater affect on performance than anything else. Counter-to-intuition, a slight imbalance of the load can yield huge performance wins.
- Most task assignment policies don't perform as well as we would like, within the limitations of our architectural model. As Feitelson et. al. [11] point out, to get good performance what we really need to do is favor short jobs in our scheduling (e.g. Shortest-Job-First). However, as Downey and Subhlok et. al. point out, biasing may lead to starvation of certain jobs, and undesirable behavior by users [9, 21]. What's nice about our `SITA-U-fair` policy is that it both gives extra benefit to short jobs (by allowing them to run on an underloaded host), while at the same time guaranteeing that the expected slowdown for short and long jobs is equal (fairness) – so that starvation is not an issue and users are not motivated to try to "beat the system." We feel that these are desirable goals for future task assignment policies.

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A Analytical Results for Distributed Server Running Under C90 Data

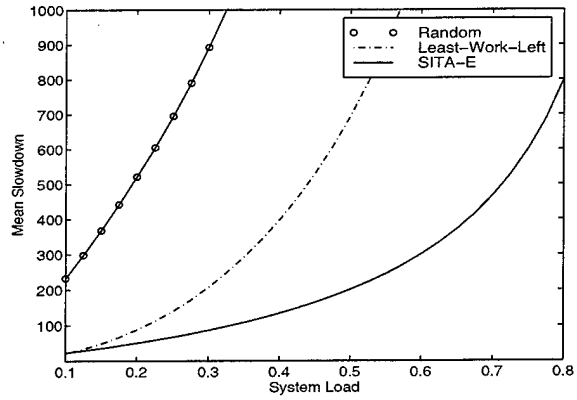

Figure 7: *Analytical comparison of mean slowdown on task assignment policies which balance load, as a function of system load.*

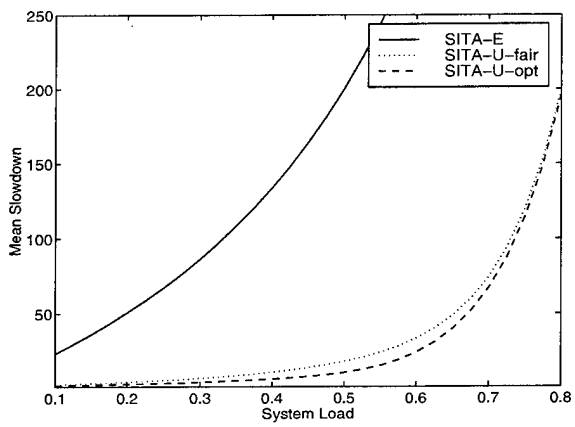

Figure 8: *Analytical comparison of mean slowdown for* `SITA-E` *and* `SITA-U-opt` *and* `SITA-U-fair`*, as a function of system load.*

B Simulation results for the distributed server under J90 data

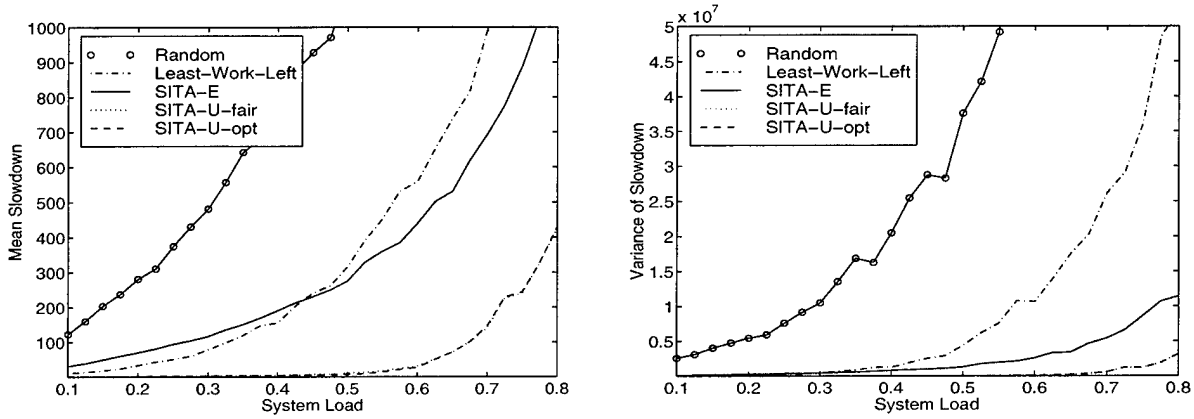

Figure 9: *Experimental comparison of mean slowdown and variance of slowdown on all task assignment policies.*

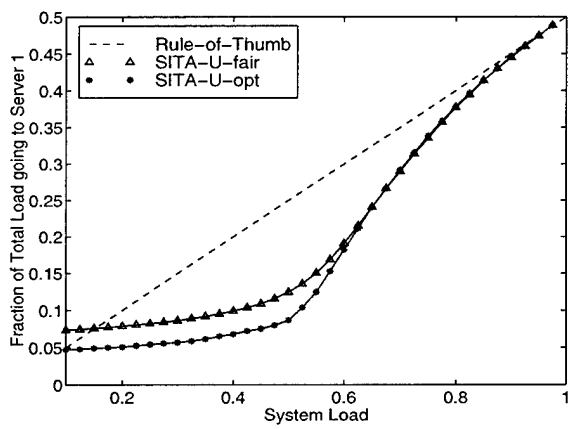

Figure 10: *Fraction of the total load which goes to Host 1 under SITA-U-opt and SITA-U-fair and our rule of thumb.*

C Simulation results for distributed server under the CTC Data

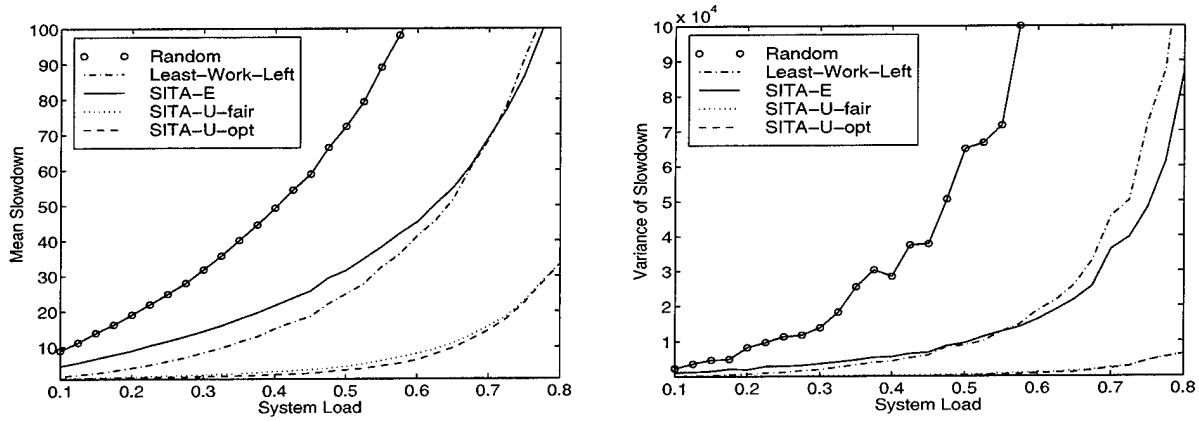

Figure 11: *Experimental comparison of mean slowdown and variance of slowdown on all task assignment policies.*

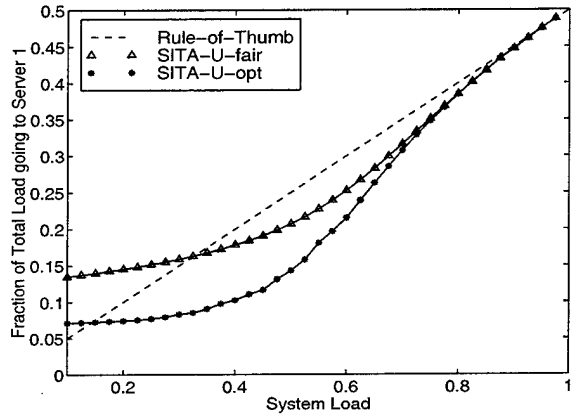

Figure 12: *Fraction of the total load which goes to Host 1 under SITA-U-opt and SITA-U-fair and our rule of thumb.*