

A Model-Based Process for Evaluating Cluster Building Blocks

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Technical Report No. UCB/EECS-2010-117

<http://www.eecs.berkeley.edu/Pubs/TechRpts/2010/EECS-2010-117.html>

August 18, 2010

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Acknowledgement

Thanks to Randy H. Katz for direction and guidance on this project and to David Culler for his valuable input. Many thanks to the indispensable Albert Goto and Jon Kuroda for their fast, effective help in getting systems up and keeping them running, Stephen Dawson-Haggerty for his help in dealing with various power meters, Yanpei Chen for initially laying the groundwork for investigating power-efficiency in Hadoop, John Davis and Suzanne Rivoire for their part in the initial cluster comparison and modeling work, Ken Lutz and the SIGCluster group for their efforts in creating an energy-proportional cluster on which to conduct research, and all the LoCal-ers and affiliates who gave feedback and encouragement along the way. This work was made possible by a fellowship from NDSEG.

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Abstract

Traditional servers account for more than 1.5% of the US electricity use though spend their lives largely underutilized or idle. Because a large portion of power in a data center is due directly or indirectly to servers, power savings in a data center environment can be achieved simply by using lower power hardware in place of these traditional servers. However, deciding which hardware to use in place of servers is complicated because lower power typically equates to lower performance and because different cluster owners use different metrics of success in quantifying cluster performance. In this project report I present measurements from several single-machine and system benchmarks for both interactive and batch jobs and develop predictive models for power and performance within a cluster. Accurately predicting power to within 10% based on OS-reported metrics requires similar training and testing benchmarks, while predicting performance within a heterogeneous web server is simple and straightforward. I also introduce a Cluster Visualizer for comparing potential cluster configurations based on the actual benchmark measurements and different metrics of value, ultimately making the decision about which hardware platform to build a cluster from less complicated.

1 Introduction

Organizations ranging from Google to university research groups to the Federal government have come to rely on data centers for their service hosting needs. In total these US data centers consumed 61 billion KWh in 2006, more than the electricity consumed by all the color televisions in the US during the same period, with an expected doubling of energy usage by 2011 [18]. While HVAC, lighting, and other infrastructure are responsible for a

portion of this energy usage, as encompassed by the PUE (Power Usage Effectiveness) metric, servers themselves consume an ever-increasing amount of energy per year, accounting for 1.5% of national electricity use within the US as of 2007. To reduce server energy usage by up to 80%, the EPA suggests some “best practices” and “state-of-the-art” solutions that include adopting “energy-efficient” servers (servers that attain high performance per expended energy), employing aggressive server and storage consolidation, and enabling power management within the data center down to the application level [18].

Aggressive power management within servers is a promising direction because, despite their high energy usage, servers tend to operate at low utilizations. A survey from Google showed that most servers tend to spend their time being utilized between 30 to 50% [2]. While this low level of utilization is reasonable in order to attain good performance and response times, these servers generally draw a disproportionately large amount of energy for such low utilization. In energy-proportional machines, in which power consumption corresponds directly to resource consumption, we would expect these machines to use 30 to 50% of their maximum power. However, we do not see this being the case in server-class machines today, with idle high-performance servers typically drawing upwards of 50 to 70% of their maximum power.

Power consumption varies between different classes of machines; traditionally, embedded systems have always considered power as a first-class constraint because they have an energy supply limited by battery capacity, so they exhibit low idle power when not in use, whereas servers have only recently started to take power into consideration. Many servers may have been designed to support various low-power S-states between “on” and “off” but cannot actually take advantage of these low power states due to a combination of board design and operating system settings.

Thus, it appears that one could attain energy savings simply from switching to lower power hardware, though this lower power often comes with a performance hit. System designers, particularly at the server level, do not typically consider energy-savings as a first-level constraint because it is a complicated matter, impacted by both hardware and software use. The first complication is that power and energy are two different quantities, despite their terms often being used interchangeably. Power is an instantaneous rate of electricity consumption, typically reported in Watts or Kilowatts. Energy is the total amount of power consumed integrated over some time period, reported in Joules or Kilowatt-hours. Thus, a high-power server that consumes twice the power of a mobile node but completes a task twice as fast will consume the same amount of energy for this task as the mobile node.

The second complication is that low power often equates to low performance in the computing world. While a cluster composed entirely of small embedded processors would have a very small power footprint, it would probably offer very low performance, a tradeoff which is not in the best interests of a business that cannot afford to lose customers because the company’s website took too long to load. Thus, traditional servers are the norm for a company trying to err on the conservative side of offering too much performance. However, there is now some interest in replacing traditional server nodes with high-performing low-power nodes.

This project report makes the following contributions: it compares performance and power-efficiency across a variety of workloads, including both interactive and batch jobs, for three different computing platforms, presents linear models for predicting power and performance within a real application, and introduces a GUI for comparing potential new clusters. Section 2 discusses related work in building and modeling power-efficient clusters. Section 3 presents three different types of hardware, four benchmarks, and the results of running the benchmarks across single-node systems of each hardware type. Section 4 then describes the two-step process for predictive power modeling and the results of this modeling for single-machine systems of these hardware types. Section 5 also predicts performance for a web server application. Section 6 discusses limitations and improvements for predictive power modeling. Finally, Section 7 introduces a GUI for visualizing the tradeoffs between power and performance of potential heterogeneous clusters composed of these underlying hardware types.

2 Related Work

A power-efficient cluster is one that attains some high level of work per unit of power consumed. The first step to building a power-efficient cluster is to select the most power-efficient building blocks, though there has been much debate about what these building blocks actually are. The authors of FAWN present a system composed of low-power, low-performance nodes and advocate for building clusters out of so-called “wimpy” or embedded nodes [1]. Interestingly, their design does not arise out of an attempt to obtain energy-proportionality and power-efficiency but instead out of the desire to create a more balanced system in which CPU speed can once again be matched by I/O capabilities. Lim et al. use simulation to select the best out of six different systems according to the metric of performance per dollar [14]. The cost part of this metric incorporates both up-front hardware

costs as well as longterm power and cooling costs. They also conjecture that higher powered CPUs may be required for CPU- and I/O-intensive workloads that would otherwise saturate CPU capacity in an embedded node. Keys et al. build and measure energy in homogeneous clusters consisting of different classes of hardware and conclude that mobile nodes and high-end servers provide the greatest power-efficiency [11]. They advocate that future clusters be built out of high performing mobile nodes.

Blade servers such as CEMS, a blade-based design of dual core Athlon desktop-class processors, have been proposed as a power-efficient cluster platform [6]. However, while highly efficient in terms of power density, it is this same density that often requires blade systems to have costly custom cooling solutions, as the rack power is higher than that in traditional servers. Substituting embedded processors in place of these desktop machines does not seem to be a silver bullet either. Reddi et al. demonstrate that embedded processors targeting the web search application space jeopardize quality of service because they do not have enough processing head room to absorb spikes in the workload without extensive overprovisioning and underutilization, though they acknowledge that smaller cores lower the total cost of ownership for a cluster [15].

A variant on the idea of power-efficiency is energy-proportionality. Barosso defines energy-proportionality as energy consumption that is proportional to the usage of some underlying resource. Thus, an energy-proportional cluster is one that uses an amount of energy that is proportional to its compute resources used. (A power-efficient cluster, on the other hand, would be one that can attain some high number of requests per expended Watt.) Building energy-proportional clusters relies on either underlying energy-proportional hardware, of which none currently exists, or the ability to fake this proportionality by turning machines on and off as workload dictates. However, data center operators and system administrators are generally averse to the notion of turning machines on and off frequently, so the experiments in this project report emphasize power-efficiency instead of energy-proportionality because it is more applicable to current data center operating conditions.

Additionally, power-efficiency has been used as a way of linking the amount of completed work to the total amount of energy used by a computing task. JouleSort uses the metric of “records sorted per Joule” to compare hardware setups for distributed sorts, but this metric is easily adapted for different workloads [17]. For instance, distributed sorts could compare total records sorted for some amount of energy, while web servers might compare the average number of requests served or transactions processed per Watt. Any of these

metrics can be easily understood and compared for a particular application.

Much attention has been paid to energy-proportional clusters acting specifically as web servers. Guerra et al. present a theoretical analysis of the potential power savings of an energy-proportional web server cluster [5]. They simulate a web server with homogeneous back-end nodes that can be turned on and off, generate request interarrival times with a Pareto distribution, and present the tradeoff that shorter interarrival times and stricter deadlines require higher energy consumption. Another study actually builds such a heterogeneous, “on-and-off” system out of power-efficient blade servers and traditional servers and attempts to minimize the power consumed per request within a web server by optimizing configuration and request distribution [7]. The creators of the NapSAC system build a power-efficient cluster out of mobile-class nodes, create a power-aware load balancer and scheduler, and compare simple scheduling algorithms’ potential power savings while maintaining SLA times [12].

Alongside energy-proportional solutions for interactive jobs are studies and analyses of how to improve energy use due to background, distributed batch-computing jobs, generally studied through the open-source Hadoop implementation of MapReduce. Leverich and Kozyrakis explore the arena of turning off underutilized nodes in a cluster to reduce power; however the distributed file system in Hadoop complicates these matters, so they add the notion of a “covering subset” of machines to ensure file availability in the course of turning machines off [13]. Chen et al. instrument a Hadoop cluster with a power meter to explore configuration effects on power such as the number of clusters used for a job and the amount of replication within a distributed file system [3]. They predict energy usage for a given Hadoop job based solely on the size of input data for the three phases of the job.

Estimating the energy used by a given job on a certain cluster configuration requires knowing the relationship between power used by the underlying hardware and its resources utilized. For these modeling purposes, prediction for power is considered “accurate” for error amounts less than 10%. Previous modeling was done strictly based on processor power, sometimes including the memory subsystem; such a model works as an approximation for how power is consumed within a system and is a better predictor than assuming constant power draw [9][8][10].

However, since the processor only accounts for a part of the total power usage in a system, considering only processor power falls short of the goal of model accuracy. This error is even more noticeable at the cluster level where errors in the single-machine model are compounded and cause wide deviations between processor-based models and actual full-cluster

power numbers. These previous, detailed models rely on hardware performance counters for their accuracy, which severely limits portability since these performance counters are not standardized across hardware and are notoriously poorly documented.

Recent studies have turned to a full-system modeling approach to model single-machine systems. Heath et al. use OS-reported metrics about CPU, memory, and disk utilization within servers to derive their full-system models, making them portable to different hardware and easier to implement than hardware performance counter-based models [7]. Economou et al. use similar OS-reported metrics to model blade and Itanium servers [4].

Rivoire et al. compare the accuracy of different modeling schemes of varying complexity [16]. Their baseline power model predicts constant power use and fares worse than the other models, which include a linear CPU-only model, a non-linear CPU-only model, and a CPU and disk utilization model, each of which uses software OS-reported utilization metrics; additionally, they compare these models against a CPU and disk software model that also incorporates four hardware performance counters. While the performance counters generally predicted most accurately across a few different hardware platforms, in a few instances the non-linear CPU-only model performed best, and all the non-baseline models had close results, meaning that hardware performance counters are not necessary to obtain accurate power models.

3 Cluster Building Block Comparisons

I benchmark three different types of hardware, each taken from one of three different classes of machines. The benchmarks include SpecPower to exercise the platforms at different CPU utilization levels, a real application (web server), and a job to exercise the whole system including disk and network (synthetic).

3.1 Hardware

From the high-performance server class, I use an Intel Xeon 5550 quad-core Nehalem server, which runs at 2.67 GHz and features 8GB RAM with a single hard disk drive. This server is one of four Nehalem servers housed in the same box with shared fans, so power measurements presented later in the report show a worst-case scenario in which three of the four processors are turned off and cannot help amortize the cost of the fans powering on.

From the mobile-class, I use Intel Atom 320 dual-core processors, which run at 1.6 GHz and are coupled with 2 GB RAM and a hard drive. While very low power on their own,

Node Type	Processor Nameplate Power (W)	System Max Power (W)	System Idle Power (W)
Server	95	229.4	196.7
Mobile	8	33.9	26.3
Embedded	0.5	4.2	3.4

Table 1: Node Power

these processors are paired with an Intel Development Board that contributes significantly to the overall power use, largely in part due to the memory controller. Both the Atom and Xeon machines run Ubuntu Linux.

From the embedded class, I use BeagleBoard systems, which feature an ARMv7 processor and approximately 245 MB of available memory. I use BeagleBoards that have their USB port enabled, which increases the power used by around 2 Watts. BeagleBoards also have a power management module available for use that could potentially cut their power use further, but I do not enable this power management. These embedded machines run Angstrom Linux.

The processor nameplate power, maximum observed system power, and system idle power use for each of these three systems is shown in Table 1. Nameplate power is the maximum amount of power a CPU can draw, as reported by the processor manufacturer. However, a processor only contributes to a portion of overall system power, with significant power draw coming from the chipset, memory, fans, and other cooling infrastructure. Additionally, the server does not draw its maximum system power all the time, often sitting idle. Hence, we require more detailed predictive power models to attain better estimates of actual system-level power use.

3.2 Benchmarks

Synthetic - This benchmark exercises different components of the system, starting with the CPU by calculating pi, then by reading and writing to disk, and finally by sending network packets. There is a period of idleness between each of these stages, which makes it very clear when these various components are being used over time. The results of this benchmark are instantaneous power readings and software counters (discussed further in Section 4.1) collected every two seconds. This benchmark is run on the mobile-class node to serve as a validating example for collecting software metrics about different system components.

SpecPower - This benchmark exercises the CPU at all different levels of utilization, from 100% down to active idle, and returns power and performance numbers. It is a Java-based workload with many optimizations available on a per-platform basis, though I use the same unoptimized program for each platform. This benchmark is run only on the mobile and server nodes, as there is not currently a good Java installation available for the ARMv7 embedded platform. These results are not considered reportable by the SPEC corporation, as I do not use SPEC-compliant power and temperature sensors.

Web Server - This benchmark is a real application meant to exercise a web server to its limits. It uses autobench and httperf to send requests for a 122K web page at increasing rates to the server under test. The results it gives include average response times, number of requests received, and number of errors. This test is run across all three hardware platforms, with the most focus given to the mobile and embedded nodes' results, the reasons for which will be discussed further in Section 4.2. Each server-under-test runs lighttpd to serve its pages, a lighter-weight alternative to Apache. In actual, highly-trafficed web servers, dynamic requests are generally filled by page caches that return static copies of the most frequently accessed pages, as is done in this benchmark which makes only static requests.

Batch Sort - This benchmark uses a Hadoop MapReduce distributed sort to represent batch jobs. The sort occurs over two main stages, a Map and a Reduce phase, with sorted data sent to other nodes over the network. As such, this benchmark is very network intensive. The total amount of data sorted depends on the number of nodes involved, with 10 GB of data allotted per worker or slave node. One node in the cluster must act as the master node in addition to its role as a worker node, which adds a minimal amount of CPU overhead to the node with a double-role [3].

3.3 Benchmark Results

The results of the synthetic benchmark show that software counters are indeed good measures of when a system resource is being utilized. As shown in Figure 1, the CPU test occurs between seconds 9 and 20 where the CPU line reaches and maintains its peak throughout the test. The write to disk part of the test occurs at second 26, and the network packets are sent between seconds 36 and 40. Memory stays constant throughout the whole test, and network packets are frequently sent and received in small numbers throughout the whole test as one would expect from a node maintaining its network presence. In addition to the scripted disk test, there are small numbers of disk writes made frequently throughout the

test due to the software metric logging. One surprising fact is that from one section of the test to the next, the power does not change noticeably. Perhaps it should not be so surprising since the mobile node has a very small dynamic power range as shown in the SpecPower results in Figure 2(a).

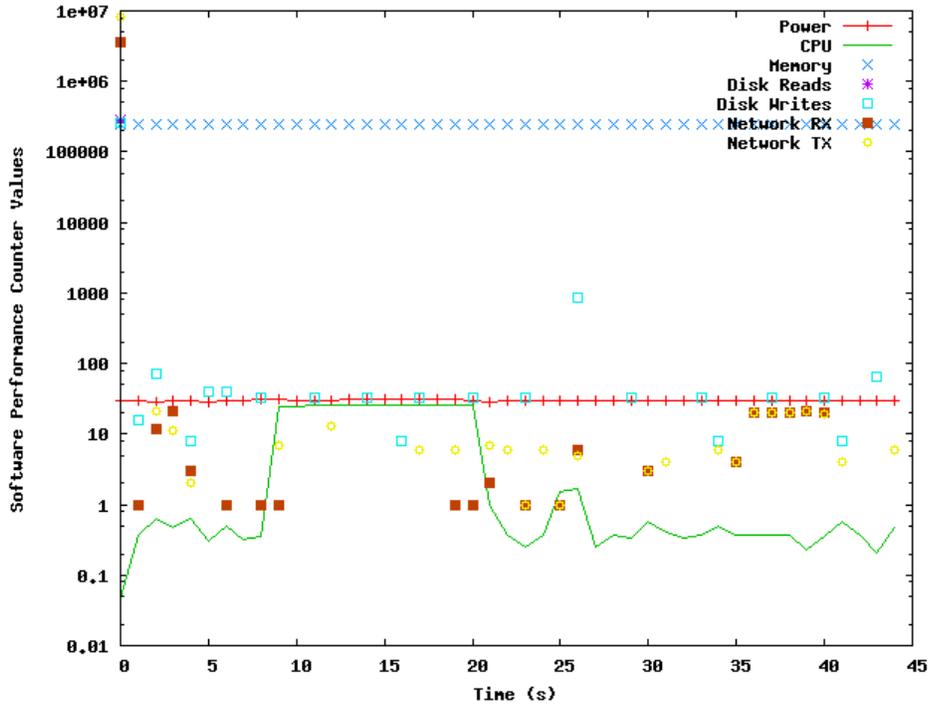


Figure 1: Software counters from synthetic benchmark in mobile node

The results of SpecPower for the mobile and server nodes are shown in Figures 2(a) and 2(b). The first graph shows the performance and power attained at each CPU utilization level, and the second graph rolls the power and performance metrics together into a single measure of efficiency at each level. These results are not normalized to the number of cores on each machine because I am interested in the total power and performance attainable with each node type. The server node takes roughly 10x the power of the mobile node though only obtains around 2x the Java performance at each utilization level. Both of these Intel processors have 45nm feature sizes and were released in close proximity around the end of 2008. While it is possible that SpecPower’s underlying code somehow favors the architecture of the Intel Atom node, it is plain to see that the mobile node has a very high performing CPU with much lower power, and as such, it has a much higher power-efficient CPU in terms of operations obtained per Watt.

Unfortunately, SpecPower results can only be shown for the server and mobile class devices, as the embedded device is ARMv7-based hardware, which at the time of this writing does not as yet have a Java implementation. As such, one can only speculate what its CPU performance and efficiency curves would look like.

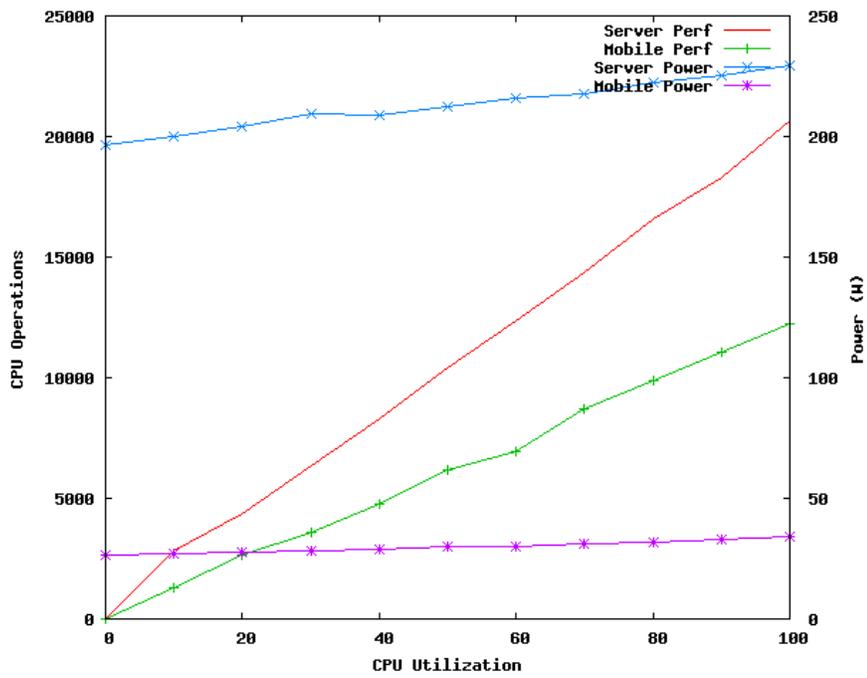
Figure 3 shows the response time versus request rate of running the web server application on each platform. The average response times for each platform are very low until the platform reaches its respective saturation point or “knee” of operation, in which the server becomes overloaded, sending response times rocketing. The embedded node can service up to about 100 requests/second before being overloaded, while the mobile node has its knee around 500 requests/second, and the Nehalem server responds well until at least 800 requests/second.

4 Power Modeling

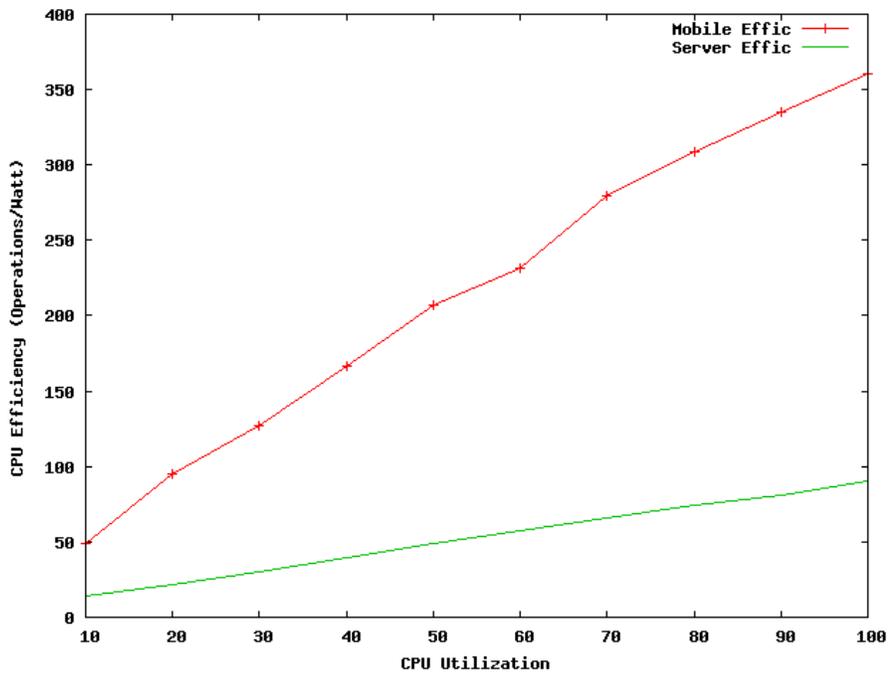
The methodology for predictive power modeling is shown in Figure 4. The first step in the modeling process is a training phase in which a benchmark runs while a collection process gathers relevant software performance counters and power measurements. These counters and measurements feed into a statistics program which calculates a linear model that best fits the input data points. The second testing step is to use these models to predict larger cluster power usage in an actual web server application. While running the application, I again collect the software performance counters, but this time, no power meter is needed. The counters feed into the linear model calculated in the training step and output power predictions.

4.1 Predicting Mobile Power for Interactive Jobs

While running each of the benchmarks, I periodically collected information from software counters kept by Linux. Every two seconds I scraped counts for the CPU usage, memory usage, disk reads and writes (all from `/proc/stat`), and packets received and transmitted via the network (`netstat`) from the time since the last measurement, in addition to the actual power readings. A significant advantage over using more hardware-based performance counters is that these software ones are available on every system. While performance counters really give a better idea of what the underlying hardware is doing (and thus where the power is actually being consumed), they differ from platform to platform and are notoriously



(a) Power and Performance



(b) CPU Efficiency

Figure 2: SpecPower Results

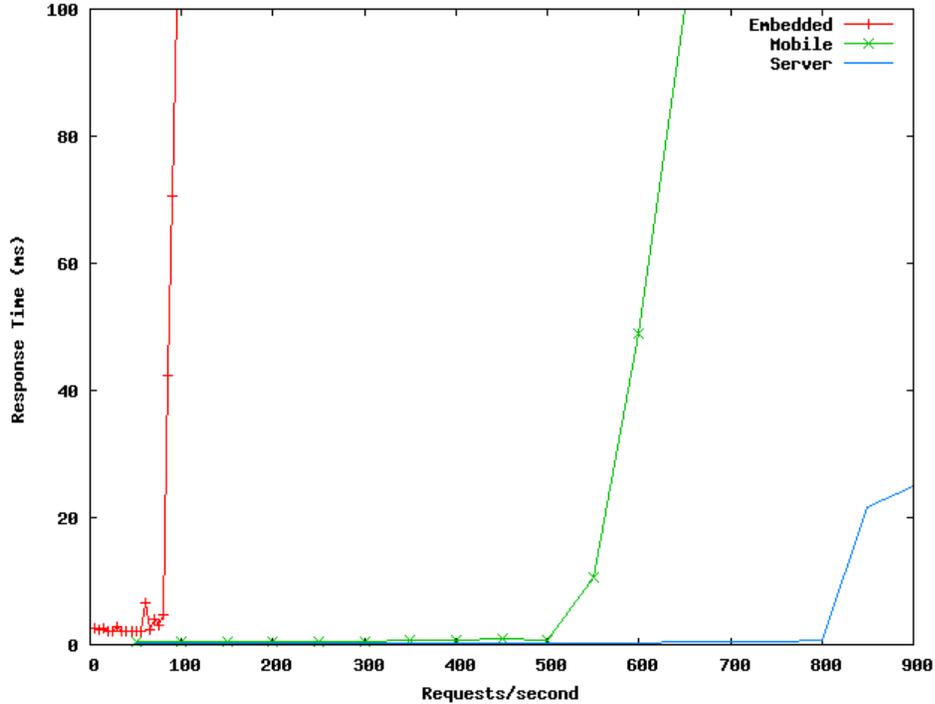


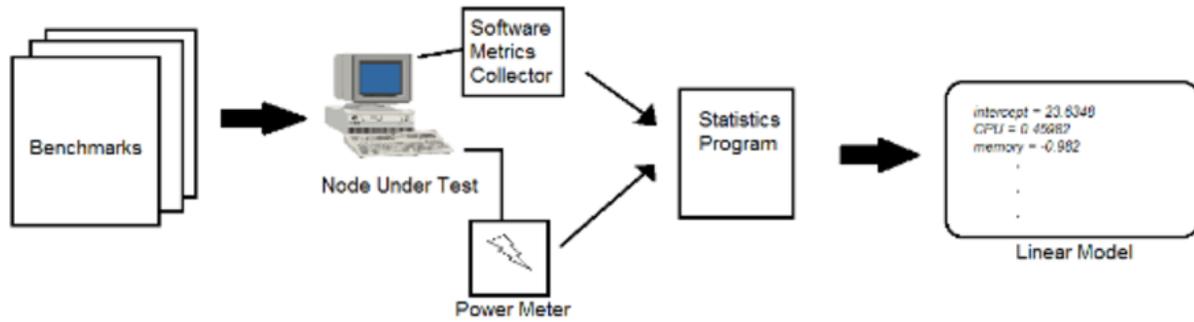
Figure 3: Response times for web server benchmark on single nodes

poorly documented. As shown in the synthetic benchmark, however, software counters do in fact give a clear idea of which resources are used; the difficult question is whether those resources are the ones that actually use the power. Modeling using software counters does not show the breakdown of power consumption on a component-by-component basis, only the relative utilization of each resource and how it correlates with overall system power.

Due to Linux’s flexibility, any number of different statistics could be gathered, but I selected these few because they are intuitive and easy to verify. Though the machines I use have a particular setup, for example, in terms of storage, the software counters should be able to account for differences in configuration related to storage or network and correlate them correctly with power readings. However, it is important to remember that every different hardware configuration requires its own fitted model. Figure 5 shows individual rates for the counters I used, where each resource’s rate is measured once per second.

These metrics were collected from a mobile node during a run of the web server benchmark with increasing request rates. As request rates rise, so does CPU usage as well as network traffic. Additionally, disk writes, due to metrics logging, are fairly constant over the benchmark, as is memory usage.

Step 1: Training



Step 2: Testing

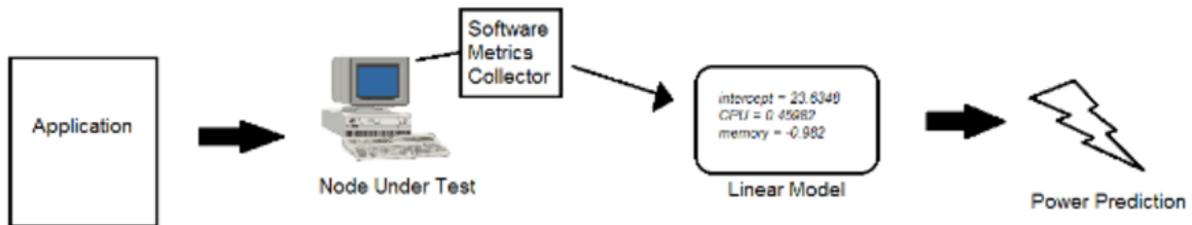


Figure 4: Methodology for Predictive Power Modeling

I then create a linear model for power usage based on the combination of the above software counters collected during an actual job run, called the training job. Modeling is done in the following way: metrics and power readings are collected once every two seconds while autobench is run. I use the open-source statistics program R to create a linear model that fits coefficients to correlate the metrics with the instantaneous power usage. I then use this model to make predictions by substituting in software counter values from an actual application run. I verified this linear model against a different run of the same workload, and then I compared the actual power used against the predictions made by different training benchmark linear models.

Selecting the best training data for use with any future testing run is tricky, as the best results likely come from a benchmark that exercises all dimensions of system resources, including processor, memory, disk, and network. From the first set of training models, I excluded the batch jobs, comparing only the synthetic, SpecPower, and web server bench-

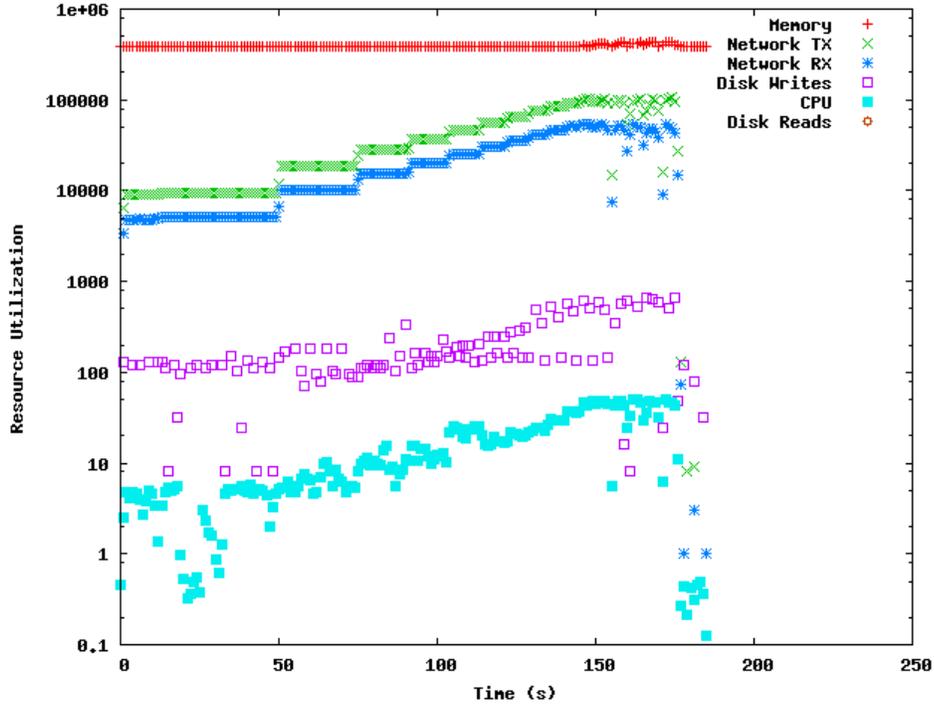


Figure 5: Software counters measured during mobile node web server benchmark

mark runs and using only the real web server application as the testing case. The web server training run gave the most accurate predictions for the web server test case. This result is not surprising because both runs are for the same benchmark that exhibits the same behavior and thus the same power usage across multiple runs. Further, the web server exercises more system components together than the other two benchmarks.

The web server benchmark was the most accurate in predicting power usage in another web server run performed on the same machine. SpecPower does worse. This result is to be expected, as SpecPower exercises solely the CPU and memory. The synthetic benchmark does the worst as a training set. This result is surprising since the benchmark exercises all the components in the system. However, it exercises each component separately, while the web server application uses many components at one time. Thus the model created for the synthetic test does not reflect the resource and power correlation of the web server test.

Figure 6(a) shows the actual power usage compared to the predicted power from each of these sets. Looking at the first graph, it is evident that the synthetic benchmark’s predictive model assigned a negative weight to the network components of the system. Thus, the model severely mispredicts power when any significant number of network packets is sent

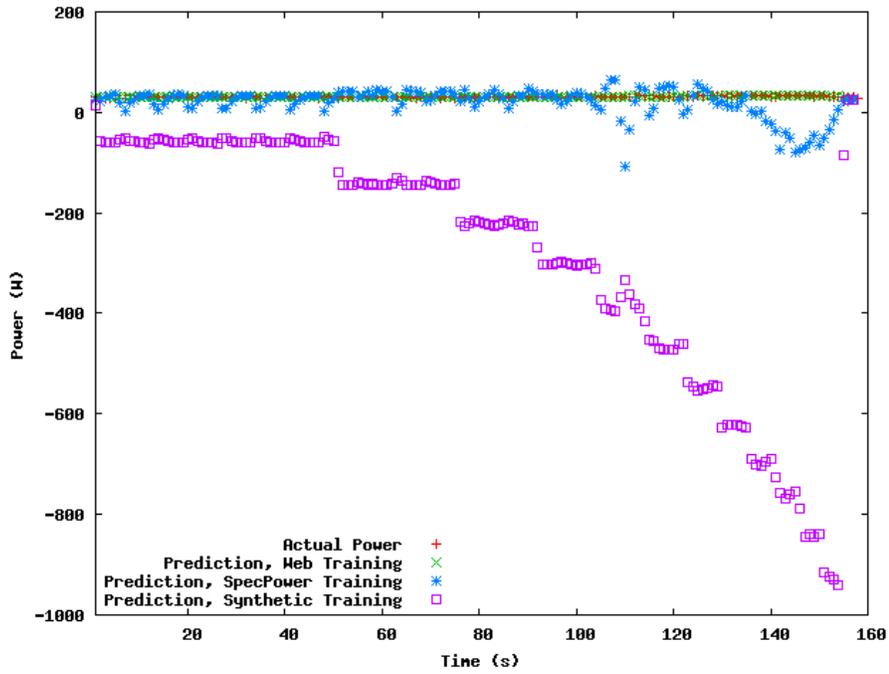
or received. Likewise, SpecPower assigned its CPU variable the wrong amount of weight for a web server test. That is, in a workload that is not strictly-CPU based, its predictions are inaccurate. The web server prediction is reasonably accurate, falling within 10% of accuracy of each measured point, which also shows that the web server workload provides fairly consistent power usage each time it is run.

4.2 Predictions Across Other Architectures

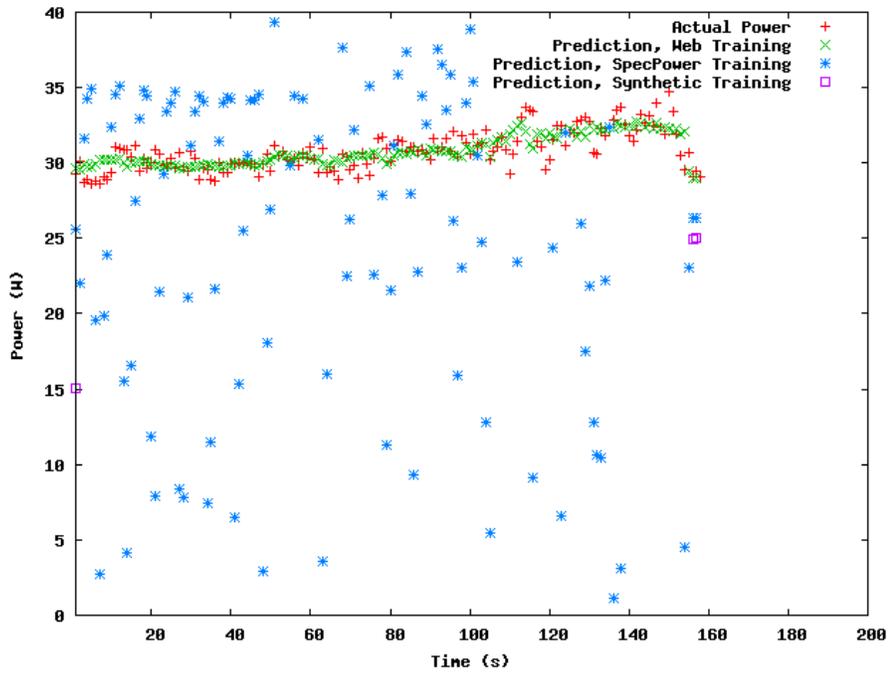
I conducted the same experiments as above on the server and embedded nodes to see if similar trends arose in the power predictions. The server node shows a large dynamic power range, stressing the accuracy of the modeling approach. Unfortunately either the underlying queueing system used by lighttpd or the pen load balancer seems to be a limiting bottleneck to performance. Thus according to the reported software counters, the server node could not be pushed beyond more than 10% of its CPU capacity by the web requests to show the maximum power range.

The different training benchmarks show similar results to those in the mobile node case. Figure 7(a) shows the results of the different benchmarks' predictions for the web server test. SpecPower does the worst in this case. This result is not surprising since the server node has a much more powerful and power-hungry CPU, meaning that a change in CPU level can signal a big change in power and should thus be assigned a large coefficient in the power model. However, a CPU-only benchmark does not work for a network and I/O utilizing job like the autobench. The synthetic benchmark does not do very well either, again because it does not utilize individual components at the same time. The web server training benchmark does remarkably well at predicting the power usage of another web server run. This result suggests that to get decent power predictions with this software counter setup, we need to train and test with the same benchmarks.

The embedded board exhibits a dynamic power range of less than one Watt throughout the entire course of the web server run, as shown in Figure 8. As such, I did not do any power prediction for the embedded board and instead focus the rest of the power modeling work on the mobile and server nodes.

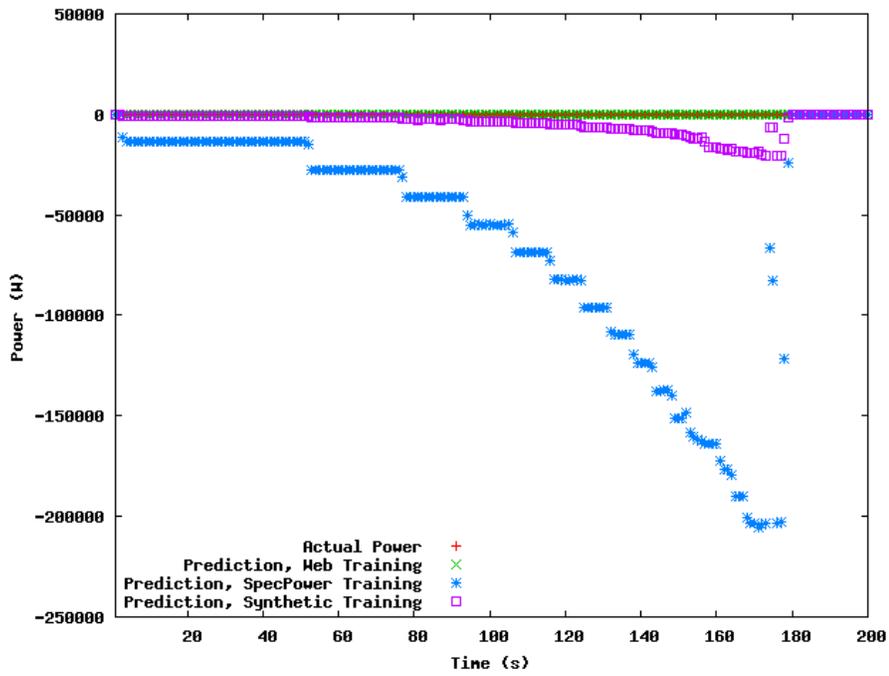


(a) Actual vs. predicted power

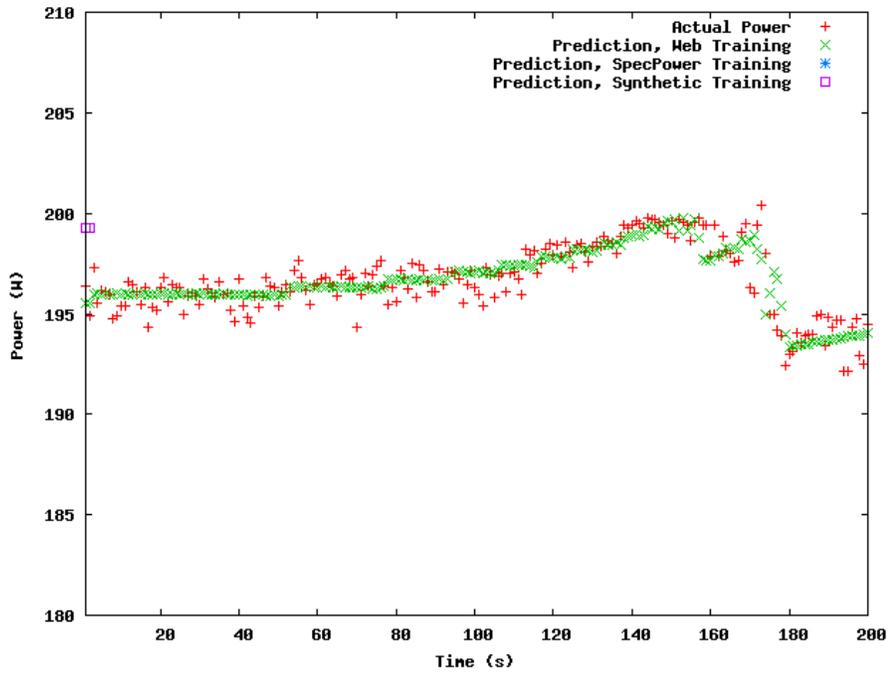


(b) Actual vs. predicted, close-up

Figure 6: Power model comparisons for mobile node web server benchmark
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(a) Actual vs. predicted power



(b) Actual vs. predicted, close-up

Figure 7: Power model comparisons for server node web server benchmark

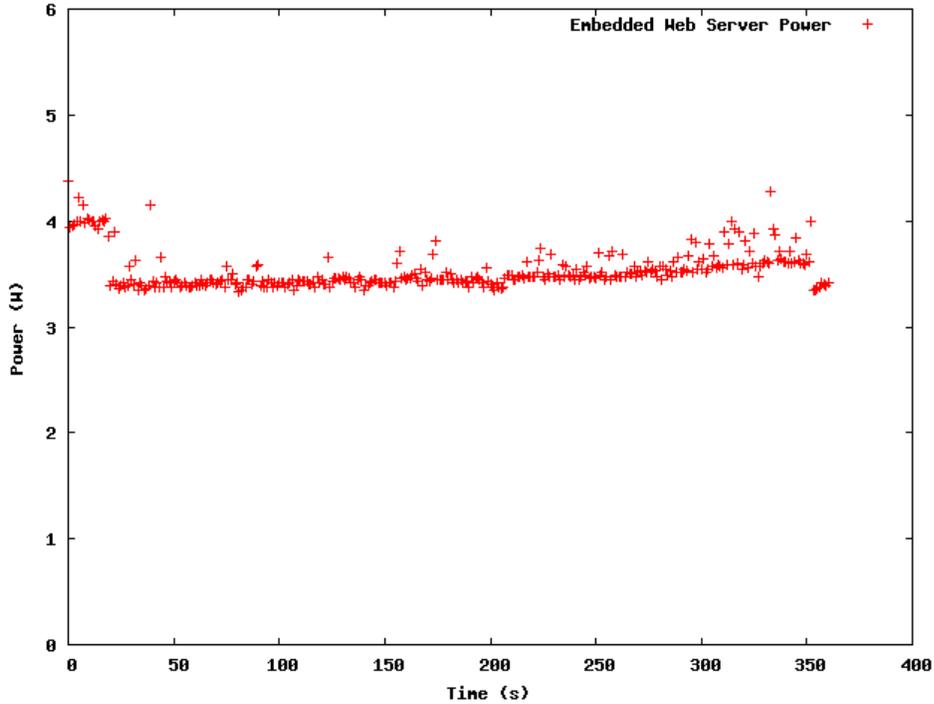


Figure 8: Actual power for embedded node web server benchmark

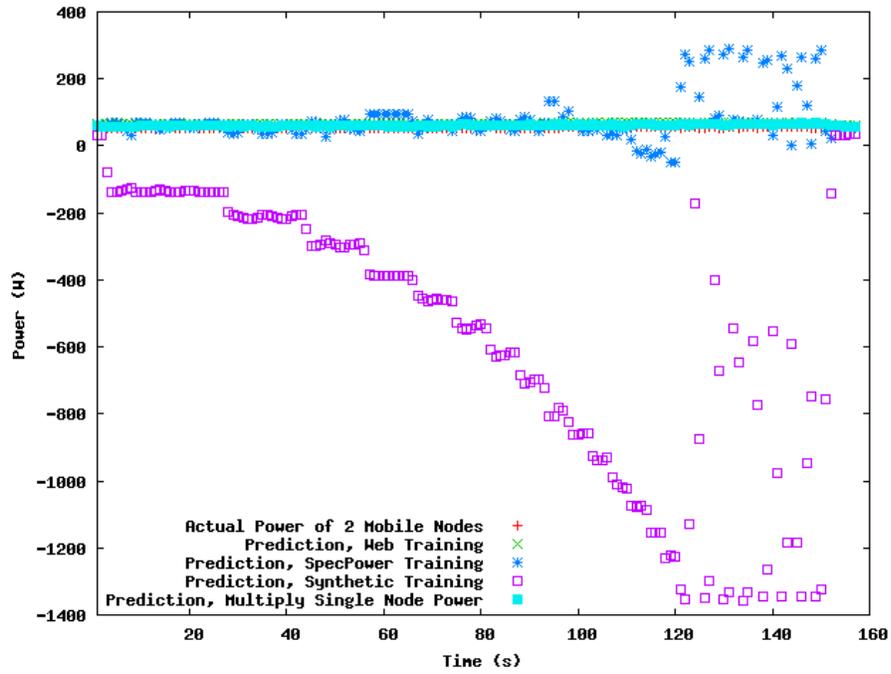
4.3 Scaling Power Predictions

Since training and testing with the same benchmark gives accurate power predictions for the single node web server test case, it seems logical to try scaling that prediction to the cluster-level. Presumably each individual machine’s associated software metrics should give good power predictions that can then be summed across the cluster. To predict at the cluster-level, I collected metrics on each of two mobile server-under-tests as well as a collated power measurement. The two mobile node servers-under-test sit behind a load balancer being run on a Nehalem server node. I ran each set of metrics through the single-node model and added the predicted power numbers together to compare against the actual power numbers obtained.

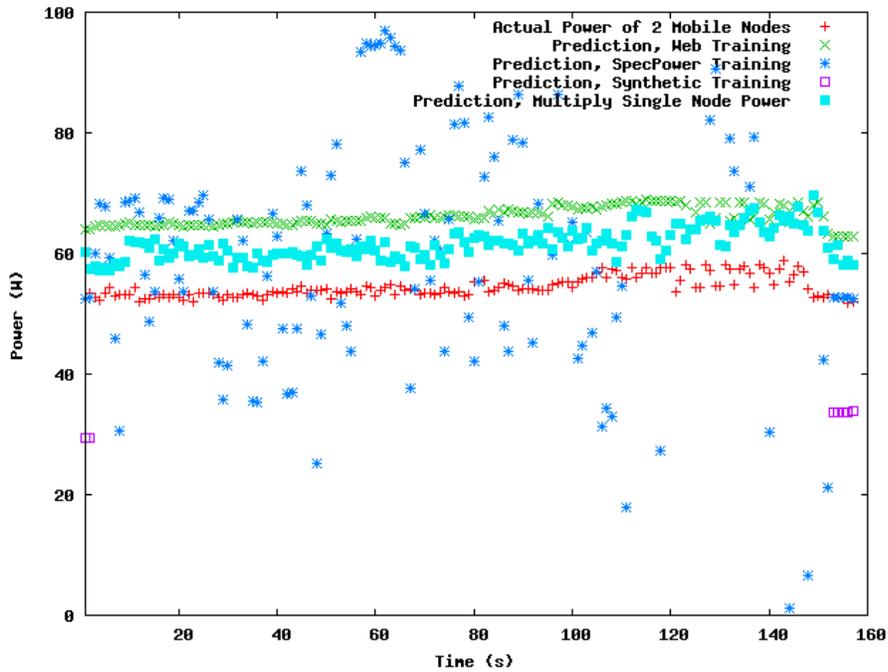
With this set of cluster-level predictions, I added in another prediction method: simply multiplying the measured power usage at each point in the single node web benchmark run by the number of nodes in the cluster, which in this case is 2. The results of these different predictions are shown in Figure 9(a). As with the single-node run, the web server training data made better predictions at the cluster level than did SpecPower or the synthetic benchmarks, and the error is compounded because of the additional node in the cluster.

However, the simple method of multiplying single node power by 2 performed even better than the web server prediction did. While the web server prediction falls within 15 to 20% of the actual power use, the multiply method reaches within 6 to 10% of accuracy at each point.

In this particular use case, requests are being distributed round-robin, thus causing homogeneous cluster nodes to have equal resource usage at all times. Workload runs with homogeneous resource usage across machines, and no modeling is necessary; total cluster usage can be simply extracted by multiplying out a single node's power usage. However, applications with unequal distribution or servers dedicated to running different applications would need individual power measurements. Batch jobs often distribute tasks across heterogeneous machines or with heterogeneous work allocations to each machine and thus provide a good test case for predicting power based on individual machine's software counters.



(a) Actual vs. predicted power



(b) Actual vs. predicted, close-up

Figure 9: Power model comparisons for 2-mobile node web server benchmark
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4.4 Power Prediction for Batch Jobs

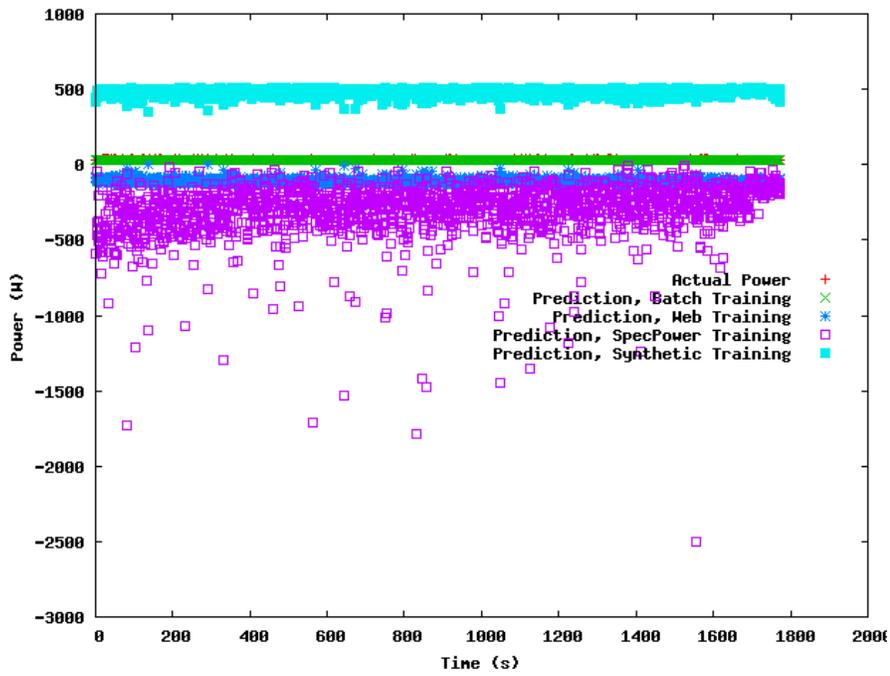
To see how power modeling fares with batch jobs, I run a 10 GB sort across a single Hadoop node and then scale it up with a sort across two Hadoop slaves nodes with one slave doubling as a master, collecting software metrics on each machine along with a collated power measurement.

The first batch run was done on a single mobile node. Figure 10(a) shows the actual and predicted power values from different training benchmarks against a batch run as the testing benchmark. As with the interactive jobs, SpecPower and the synthetic benchmark provide poor predictions for the sort job, though the web server application also joins the ranks in predicting poorly for this job. Figure 10(b) shows that only the batch job does the trick of predicting power accurately, hitting the average power usage throughout the whole test and falling within a few Watts of accuracy at every point. However, since the mobile node only has a small dynamic power range, it is prudent to consider the server node with a wider power range as well.

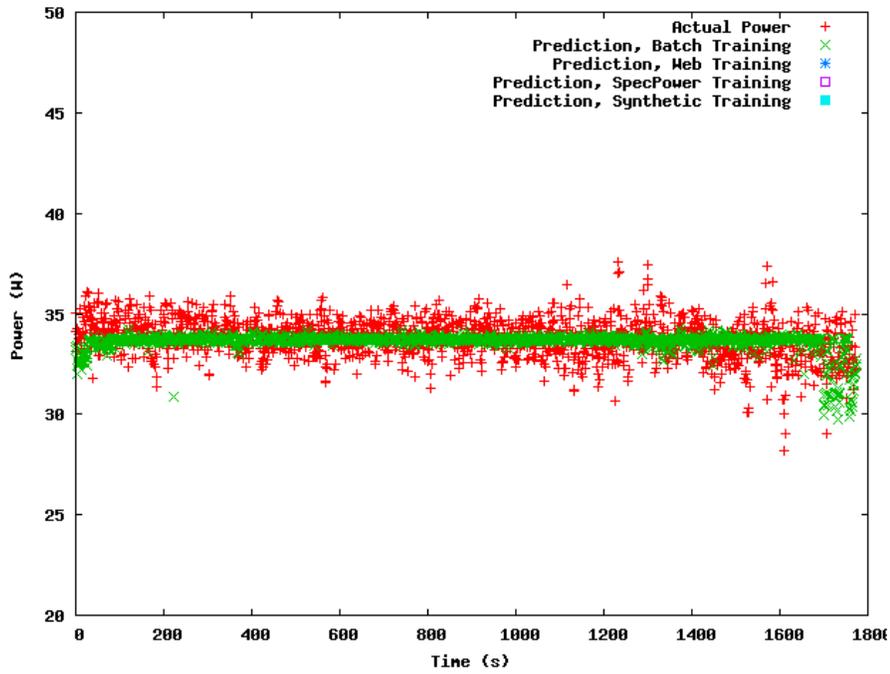
The server node exhibits the same behavior, however, with Figure 11(b) showing how closely the batch training job predicts a different batch testing run with none of the other three benchmarks even coming close. Additionally, this figure clearly shows the different power usage for the Map and Reduce phases of the job, with the Map stage completing around 400 seconds into the run.

To test power prediction at the cluster level for batch jobs, I ran a sort across one server node and one mobile node together, with the server node acting as the combined master and slave node. While two servers would have had a greater power range, the shared fan infrastructure of the servers described earlier would not have allowed for clean predictions, so I used two completely separate nodes that also happen to be heterogeneous.

The results in Figure 12(a) show a slightly different profile than any previous ones. While the batch training job from individual nodes comes closest in accuracy for its cluster-level predictions, the results are not nearly as close as in scaling up the interactive job. So what changed? In this case, the answer is network traffic.

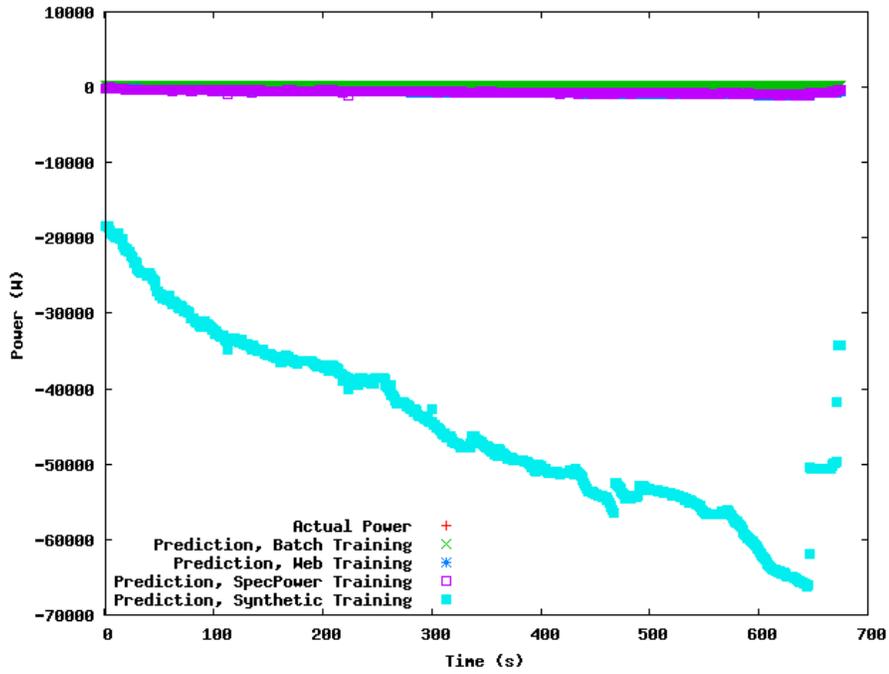


(a) Actual vs. predicted power

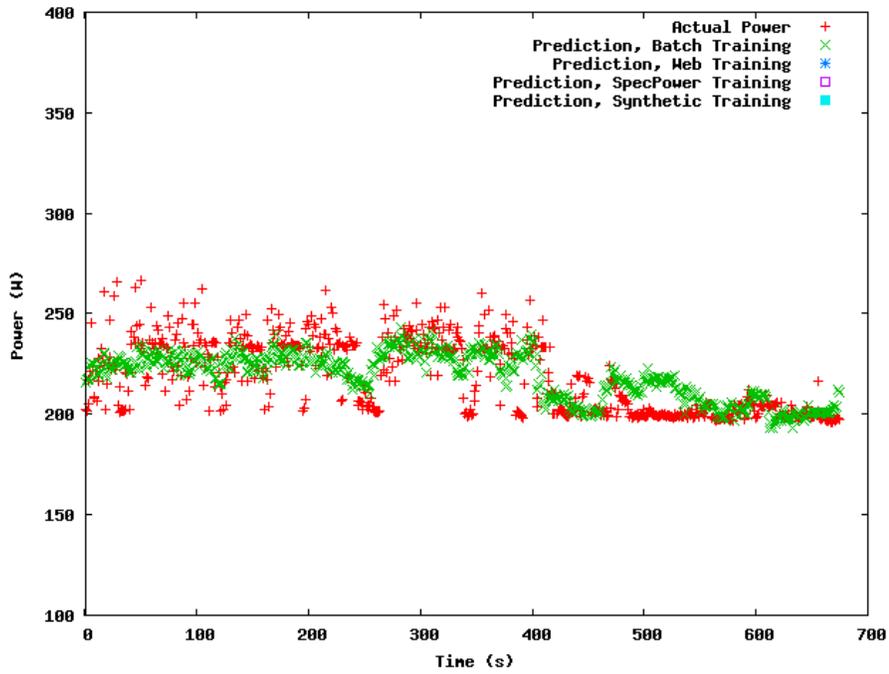


(b) Actual vs. predicted power, close-up

Figure 10: Power model comparisons for mobile node batch sort
22

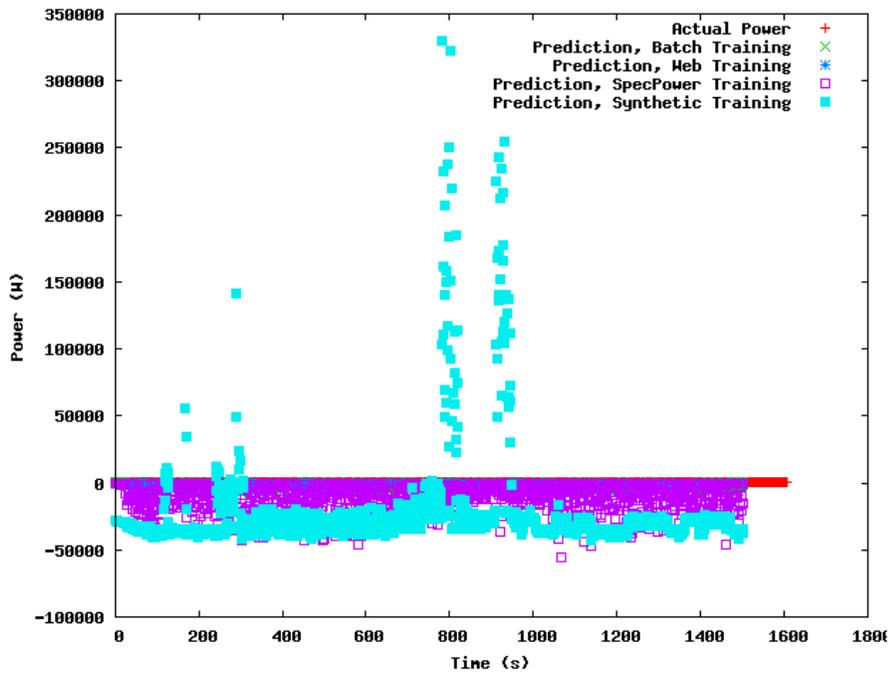


(a) Actual vs. predicted power

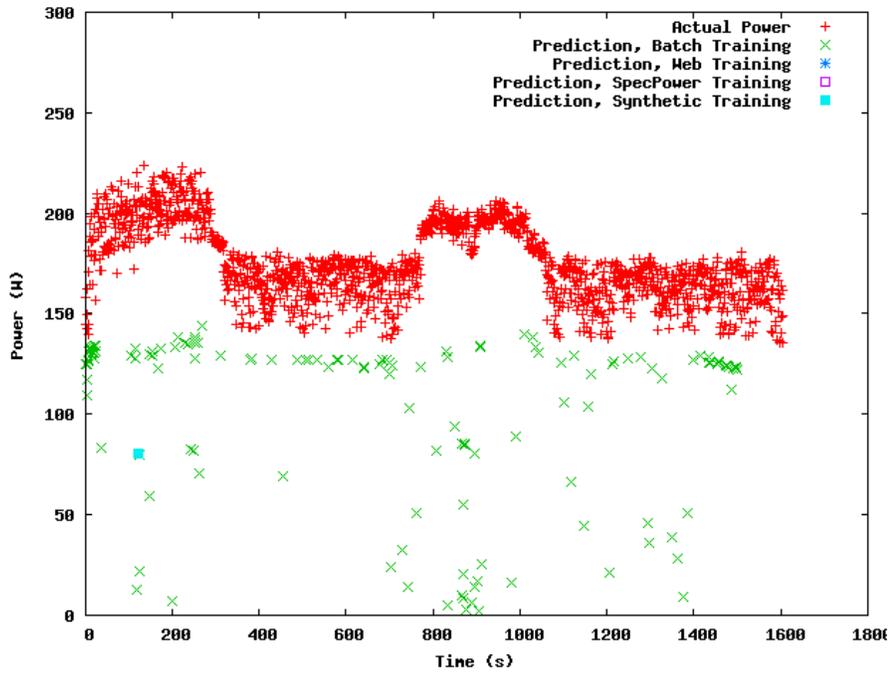


(b) Actual vs. predicted power, close-up

Figure 11: Power model comparisons for server node batch sort
23



(a) Actual vs. predicted power



(b) Actual vs. predicted power, close-up

Figure 12: Power model comparisons for mobile+server cluster batch sort
24

The single node sort jobs created power models without doing any of the requisite network sending and shuffling associated with a multi-node cluster sort. As such, even though each node was doing exactly the same work with an added sending step, the power predictions are different. In essence, scaling up a batch sort from a single node to multiple nodes is almost like running two different programs, at least from the perspective of utilized resources. When interactive web server tasks are load balanced across multiple machines, each machine does the same thing it did as a single node without additional steps.

Based on scaling up both interactive and batch job power predictions, there is a big conclusion we can draw about power modeling using Linux software counters: to get accurate power predictions, it is important that the training program be very similar to the testing program. If the profile of resource utilization of any parameter in the linear model changes significantly from training to testing, the results will be very skewed. In the case of the batch job, since the server node was responsible for dealing with the network shuffling part of the sort, its network packets soared, while its overall power didn't change that much from its original power use. However, the linear model for the single-node Hadoop server scenario assigned a coefficient value to the network activity that assumed a low level of network traffic, so the prediction is totally off in a true multi-node system.

5 Modeling Web Server Performance

In scaling up a cluster, we must consider both how power scales and also how performance is affected by the addition of nodes. In the case of the real web server application, performance is measured by average response time, which could be particularly affected by the addition of heterogeneous nodes.

I used the afore-described web server setup with autobench and lighttpd to fetch a given file at increasing rates to find the “knee” of a cluster, or the rate at which the response time increases exponentially, in addition to the average response times. The architecture for the load balanced web server is shown in Figure 13. Each machine under test sits behind the open-source load balancer *pen* on a Nehalem server, and the web workload is generated on an additional machine. *Pen* adds minimal overhead at the request rates sent to the individual machines.

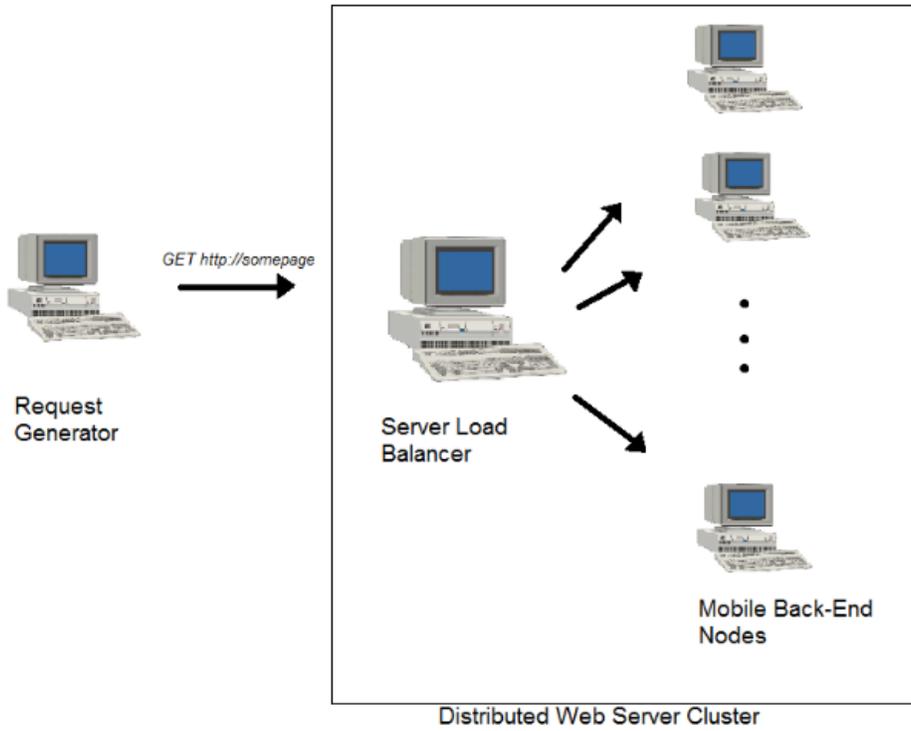


Figure 13: Architecture of Web Server

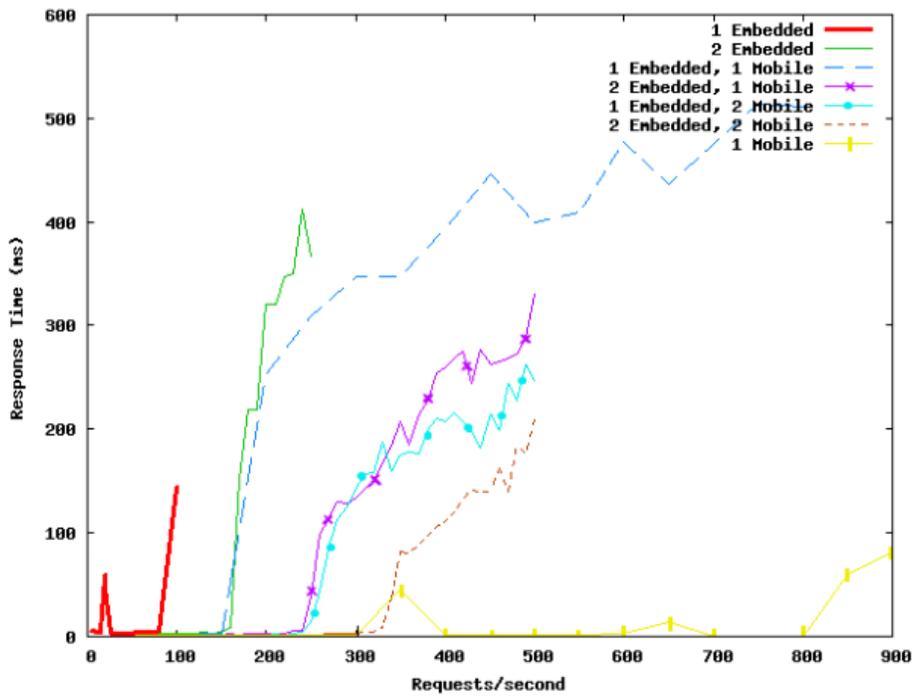


Figure 14: Response times for different clusters running web server benchmark

As shown in Figure 14, response time is largely determined by the “weakest,” lowest-performing member of the cluster. Cluster setups with embedded nodes have their knees at much lower rates than those without embedded nodes. Additionally, clusters with embedded nodes have higher knees as their overall cluster size increases. The new cluster knee will occur at $n * \{\text{the knee rate of the weakest node}\}$, with the knee’s slope increasing more gradually the more nodes n there are in the cluster. This knee makes sense because in a round robin style cluster, one out of every n requests are being sent to each node, meaning the earliest individual node to reach its knee rate k will occur at the overall cluster request rate of $n * k$. Even though the weakest machine’s response time will be increasing exponentially, the remaining $n-1$ nodes help to reduce the average response times slightly, meaning that sufficiently large numbers of machines can help hide the latency imposed by a low-performing machine.

For higher numbers of n , the slope of the knee will increasingly lessen as the weakest machine gets requests less often in round-robin mode, though this cannot be shown for sufficiently high number of requests due to limitations of the load balancer, as discussed in Section 6.

The average response time reported by `httperf` can be approximated as follows: the average response time at a given rate is the average of the response times across all the machines in the cluster for the rate at $1/n$ th the total cluster workload rate, that is, at the incoming rate each individual machine sees.

For a given rate r and n total machines,

$$avgR(r) = \frac{\sum_i^n R_i(\frac{r}{n})}{n} \quad (1)$$

Figure 15 shows the average response time prediction using Equation 1 versus the actual average response times for two different cluster setups. The first cluster setup is composed of two embedded nodes, and the second is one embedded node and two mobile nodes. The predicted response times very closely approximate the actual response times, though the slope of the actual response times seems a bit smoother than the slopes of the predicted times. This discrepancy requires further study though is likely due to the presence of a load balancer, with overloaded nodes able to empty their queues slightly during micro- or millisecond delays introduced by the load balancer, thus reducing the average response time by a few milliseconds.

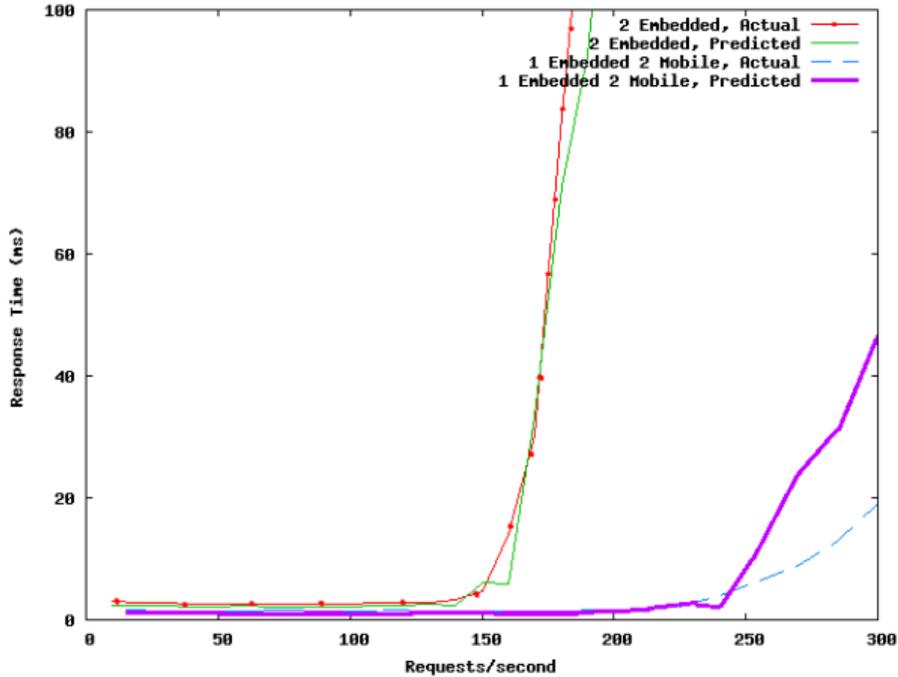


Figure 15: Actual vs. predicted response times for clusters running web server benchmark

The knee of a cluster will be higher if machines are given requests in accordance with their maximum capacity or based on other weighted or “sticky” scheduling algorithms. Because the weakest cluster member is responsible for increasing overall response times, the optimal technique for maintaining good response times is to keep machines with the highest knee loaded up to capacity and then adding smaller machines to be kept lightly loaded. This approach is used in the scheduler for the energy-proportional NapSAC web server cluster, which uses heavyweight Nehalem servers to handle the bulk of requests and less powerful mobile and embedded nodes to handle occasional workload spikes [12]. For applications in which round robin is not the scheduling algorithm used, a weighting factor can be incorporated into the rate equation.

6 Limitations and Improvements

With regards to predicting instantaneous power, the models can only be as accurate as the power meter allows them to be. Unfortunately, this particular power meter collects data only once every two seconds, so it’s impossible to get finer-grained detail, and its timing doesn’t match up with the workload-generating, log-recording machine, meaning that the

number of metrics and power readings do not match up exactly, which makes it difficult to create an accurate model as some readings must be thrown out. Synching up the CPU and power meter is sadly out of my hands, as I do not know of any way to calibrate the timing on this power meter. The description of the power meter as taking readings “every two seconds” is fairly generous, as it does not seem to maintain a reliable two second interval, with variations of milliseconds building up with each measurement. I can only assume that the actual Watt measurements it provides are accurate at all levels, as I have not physically calibrated it myself.

Improving the actual power model for predictions where nodes are not equally utilized could entail splitting up the model into two parts, one to handle the high end of the CPU spectrum and the other to handle the lower half, based on some empirically discovered inflection point. Additionally, different methods of measuring the CPU utilization or measuring at longer intervals is also possible, though the latter option doesn’t seem to help much due to the afore-mentioned power meter limitations. Realistically, improvements to power modeling simply cannot happen without first finding a top-notch power meter.

Non-linear models, particularly within certain components like the CPU, seem to be pointed at by work by Rivoire et al. Also, CPU utilization on multicore machines is measured based on average combined utilization across all cores, so different cores are at different utilization levels. It would be possible to add additional counters for each core, but the models using similar training and testing workloads are accurate enough without these individual counters.

Turning to performance modeling, the load balancer is itself a limitation. It has an inherent limit to how many requests it can handle, based on operating system settings, link capacity, and CPU capabilities of the hosting machine. Ideal load balancing allows us to find the knee of cluster operations, but available load balancers often fall short of this expectation without significant tinkering and recompiling of the OS. We are ultimately limited by the underlying machine running the load balancer, so the solution to this problem is to use a high-performing machine to load balance, or better yet, to use many machines together as a load balancer. Finding the actual cluster knee would require a much higher performing node, so I conducted my load balancing experiments with the smaller capacity embedded and mobile nodes and hope that their behavior generalizes to the server class. It is impossible to do any experiments over 850 requests/second, though it is hard to say whether this limit is due more to the load balancer’s lack of robustness or the actual server node itself (though the overhead associated with using the load balancer appears to be fairly

minimal at low request rates).

7 Visualizer

7.1 A Tool for Visualizing Energy-Aware Configurations

The above benchmarks and tests show that cluster energy usage varies drastically depending on the individual components it is composed of due to different power and performance capabilities of the individual cluster building blocks. To make it easier to see these differences before actually having to physically build and test a cluster, I present a Cluster Visualizer GUI.

The Cluster Visualizer (CV) presents a listing of all the available machines that could be added to a cluster. By clicking on these available machines listed at the bottom of the screen, the user adds these machines to their current cluster configuration, which is shown in the middle of the screen. Machines can be removed from the current cluster by clicking on their icon in the middle of the screen. Once machines have been added to the cluster configuration, one can view metrics about the cluster, including cost, CPU power, performance, and efficiency at different utilization levels, and web server response times. A cluster configuration can be saved and loaded again at a later time. This single cluster creation mode is shown in Figure 16.

Clusters can be created in one of three different modes: unconstrained additional nodes, limiting based on power, and limiting based on cost. In unconstrained mode, any set of available hardware can be added to the current cluster configuration. When configurations are constrained by power, the user inputs some number of Watts to limit their cluster based on (provisioning based on a given power envelope, as is done in data centers). New nodes can only be added to a cluster configuration if their maximum power falls within the cluster's total power envelope. Likewise, creation limited based on cost only allows nodes to be added to the cluster if their hardware cost falls within the total user-specified budget.

The CV also provides a comparison mode where two cluster configurations can be compared along the same metrics. The user need only switch over into Comparison Mode, shown in Figure 17, build or load two cluster configurations, and compare along the aforementioned metrics. Thanks to the hardware models described in the above sections, accurate predictions about power and performance across multiple machines can be shown based on single machine application runs.

Cost of machines comes from user-input upon initial addition of a new hardware profile.

CPU power use at different utilizations comes from the measured power meter readings during the SpecPower benchmark. The power used by a cluster of machines at a certain level of utilization is estimated by adding the power for each individual machine at that level of utilization; while this measurement will only be accurate if machines are actually given equal shares of a workload, it is more valuable as a relative measure between two clusters' power use. The CPU performance number of Java operations at a given utilization is a summation of the total operations each machine in the cluster can undertake in the SpecPower run. CPU efficiency comes from dividing the power by the performance numbers given by the SpecPower benchmark. The web response times for a cluster are derived using Equation 1 to average response times measured on individual machines using the web server benchmark. Thus, all the predictions and numbers presented in the CV are based on actual measured results.

Information about the embedded, mobile, and server nodes tested throughout this project report is available for use in the CV, so all the power and performance numbers are accurate and usable. Adding new hardware is very simple, requiring single-machine runs across a few benchmarks. Every type of hardware represented in the CV requires a CSV file containing the results of these benchmarks (further discussed in Section 10), which can be parsed and gathered with an included program. Adding more applications or metrics to compare along is slightly more complicated though also easy, requiring a few additional functions in the Python GUI code as well as new entries in each hardware profile.

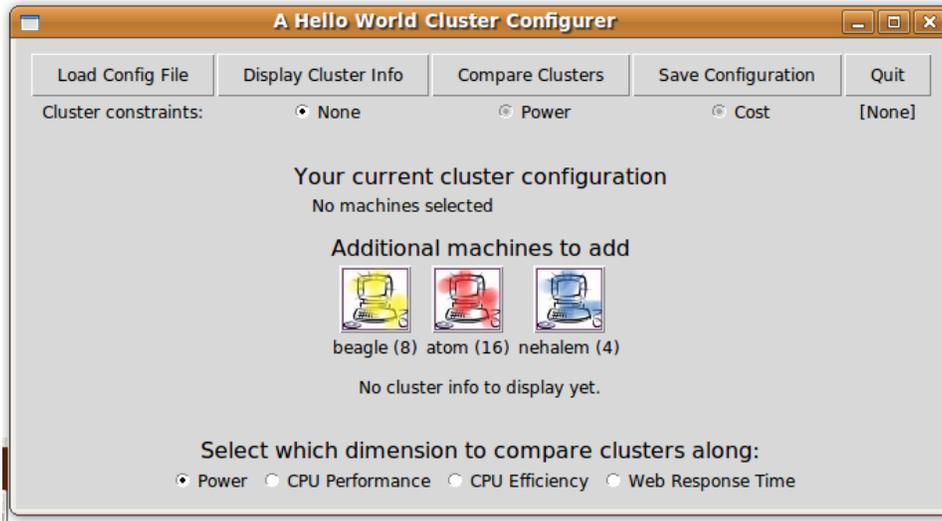


Figure 16: Cluster visualizer in single cluster mode

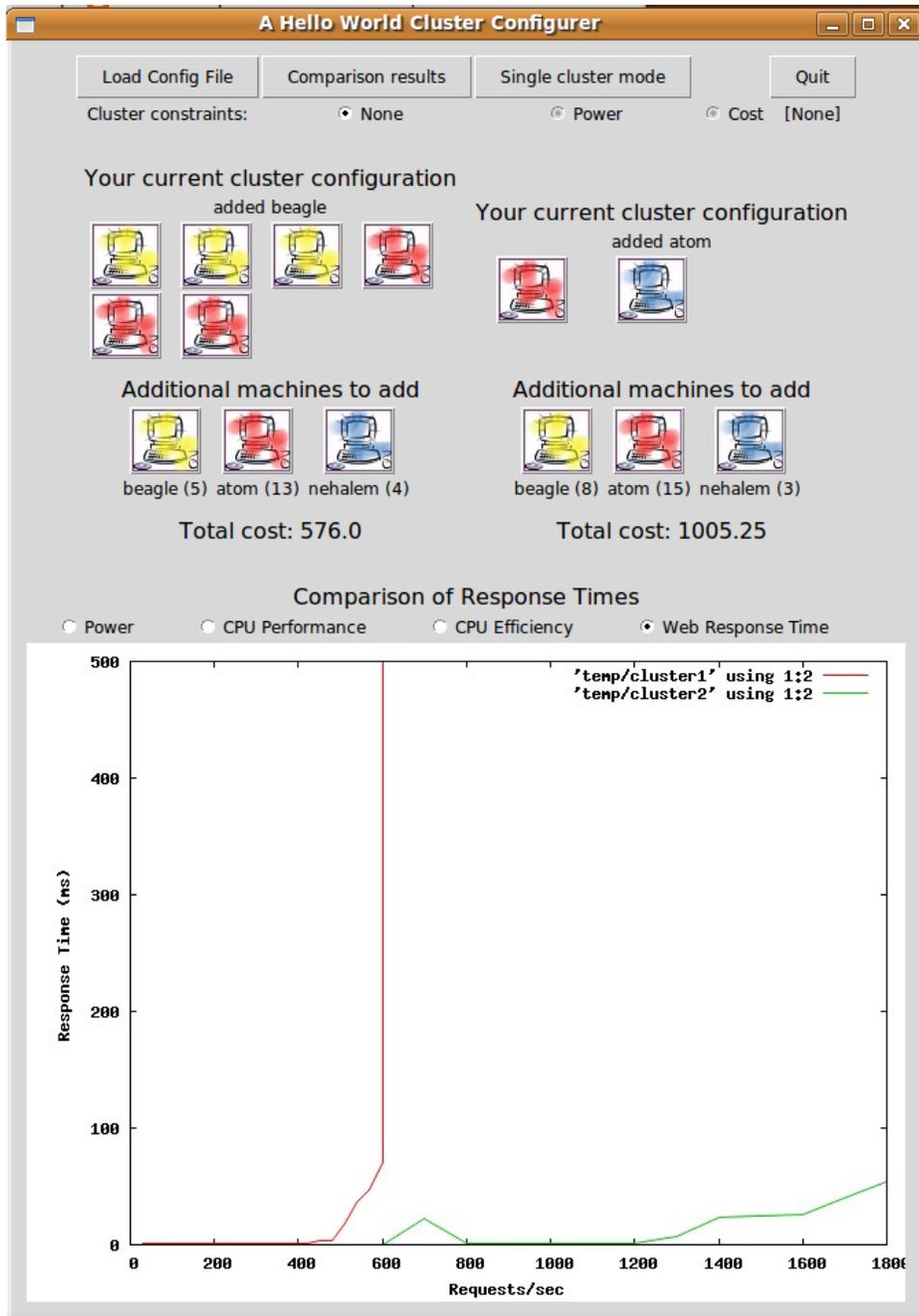


Figure 17: Cluster visualizer in comparison mode with web response times

7.2 Example Use Case

To show how the CV can be used in deciding between two clusters based on different metrics, Figures 18, 19, and 20 show the actual comparison between two potential computing setups. Cluster configuration is limited based on cost in Figure 18 to \$1,000. The left-hand cluster consists of one Nehalem server, and the right-hand cluster consists of 9 mobile Atom nodes and 4 embedded Beagle nodes. By comparing them in Figure 19, we can see that power is higher in the multi-node cluster by about 50 Watts or 25%.

However, this same multi-node cluster attains higher total CPU performance than the single server, meaning the multi-node cluster has magnitudes greater CPU power-efficiency as shown in Figure 20. Likewise, as a web server the multinode cluster has a higher knee than the single Nehalem server. By these metrics the multi-node cluster appears to be a better buy than the single server, though additional metrics such as additional networking wiring and setup might present a different picture.

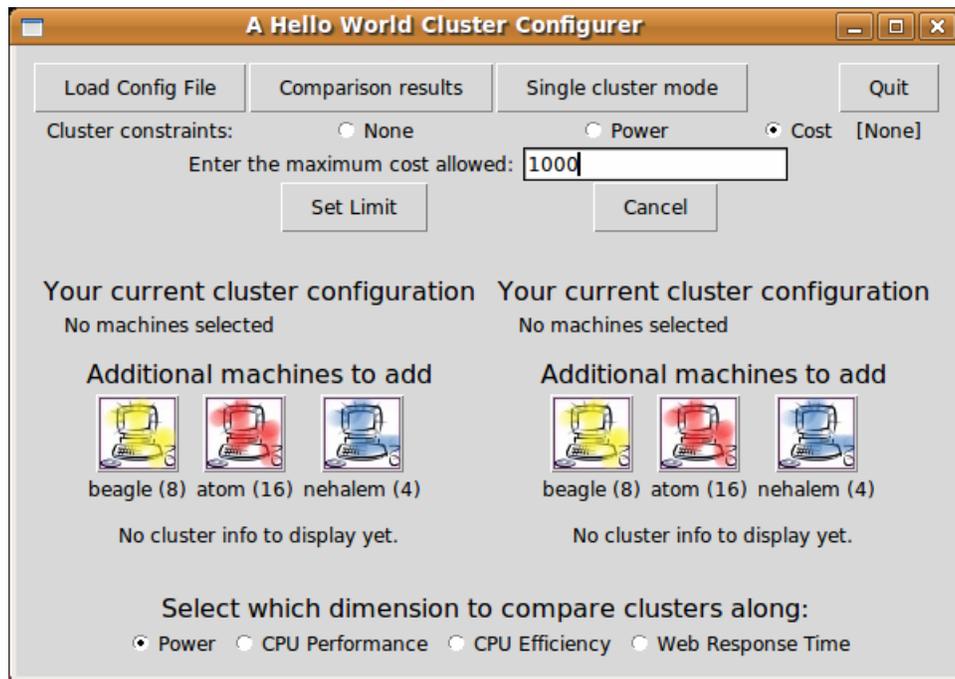


Figure 18: Configuring clusters constrained by hardware cost

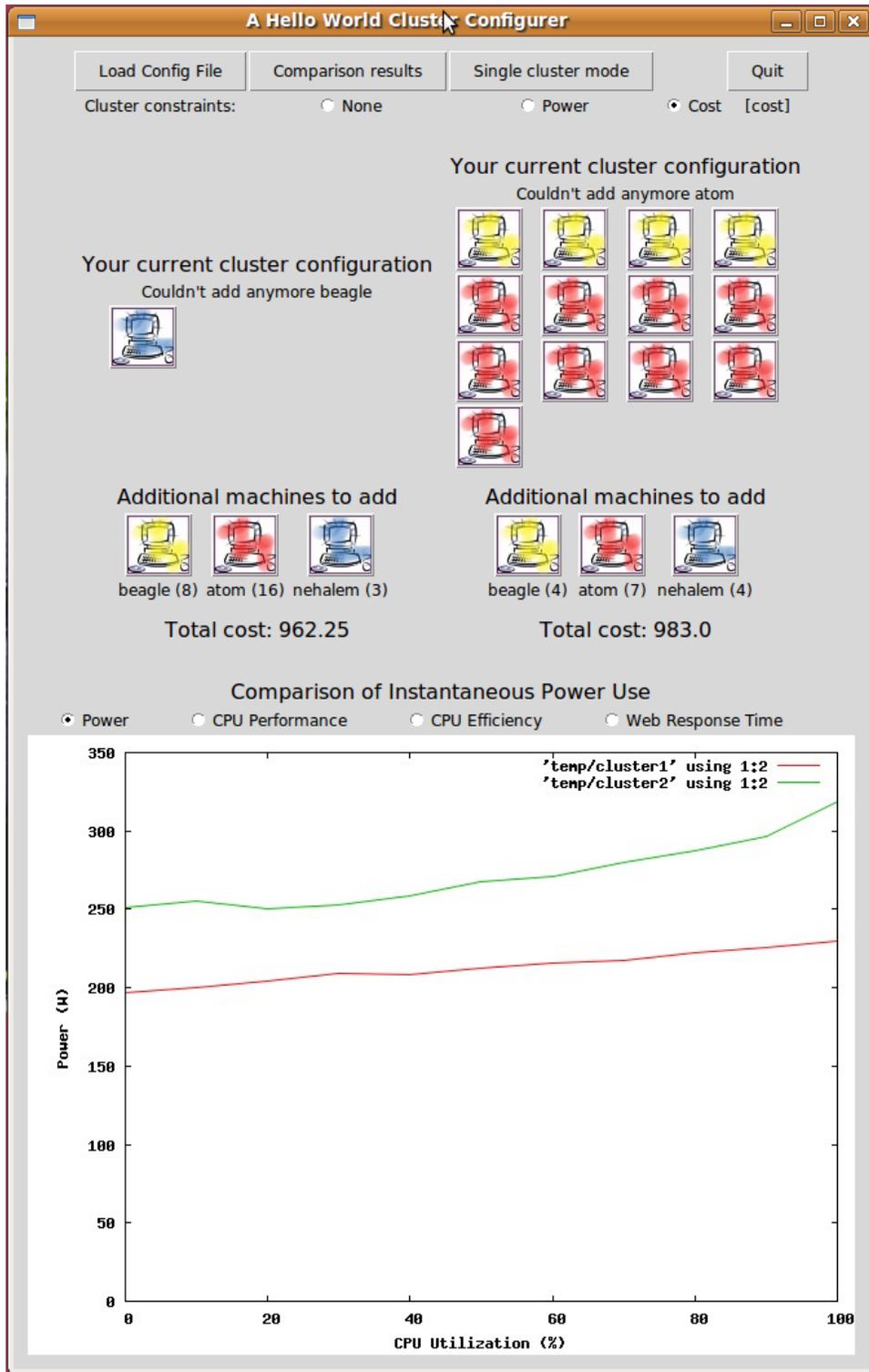


Figure 19: Cluster visualizer for actual use case comparisons across power

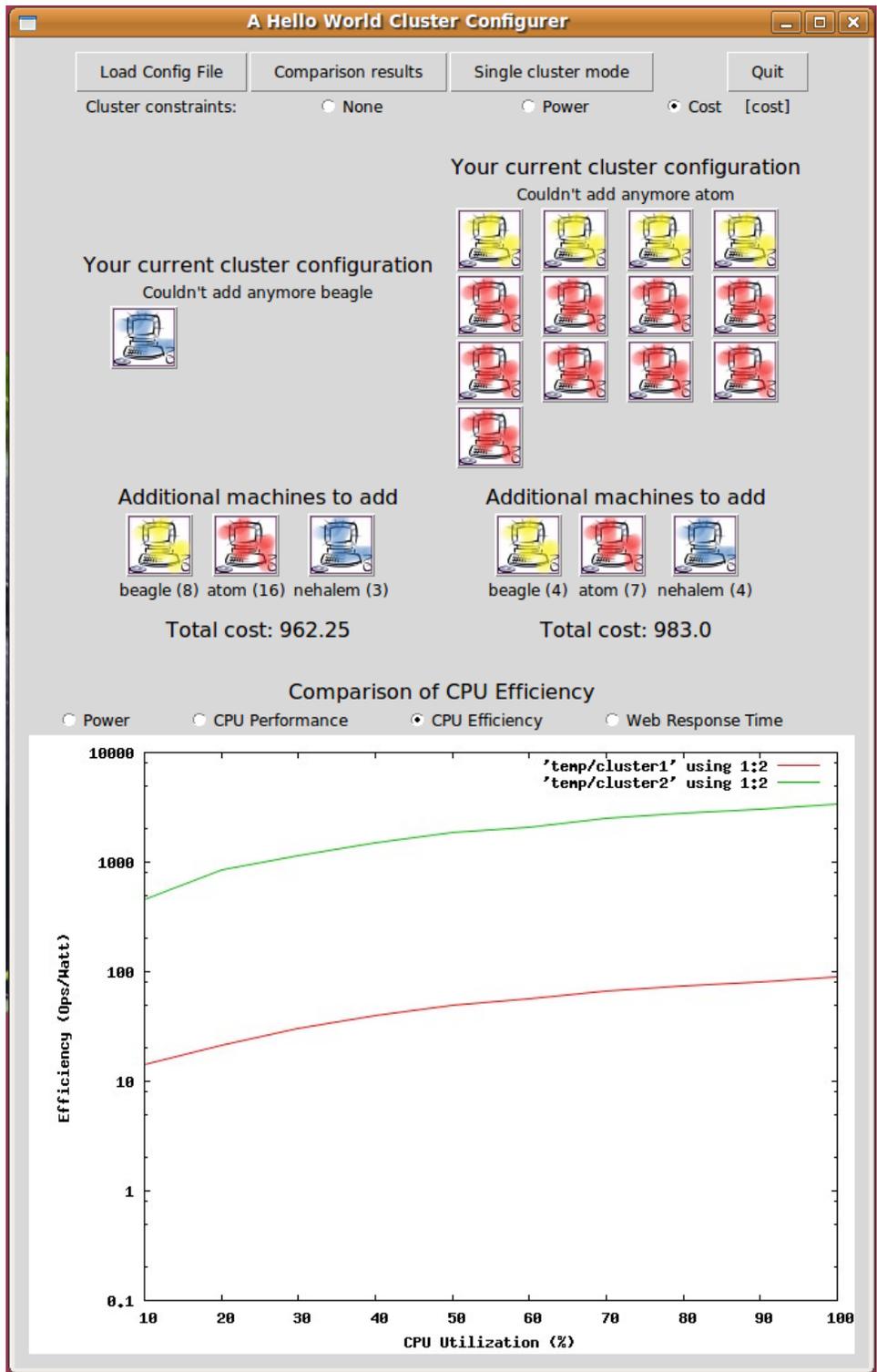


Figure 20: Cluster visualizer for actual use case comparisons across power-efficiency

8 Conclusion

Servers in distributed computing environments spend around half their time being lightly utilized or idle, but they consume more than half of their maximum power in these periods of low utilization. Thus, power savings in a data center can be achieved without turning machines off simply by replacing these traditional servers with lower power hardware that will waste less power when idling. However, deciding which hardware to use in place of servers is a difficult decision partly because lower power typically equates to lower performance and also because different cluster owners use different metrics of success in quantifying cluster performance.

I compared three very different types of hardware across a few benchmarks: an ARM-based embedded board, an Intel Atom mobile node, and a Xeon server. A selection of single-machine benchmarks helped build up a profile of each type of hardware, including the CPU-intensive SpecPower, a full-system synthetic benchmark, the web server autobench, and a MapReduce batch sort. Comparing the three systems across power use, traditional performance, efficiency, and response times, the mobile node exhibited the highest efficiency by using considerably lower power than the traditional server while still being able to maintain reasonable performance.

From these single-machine benchmark runs, I created a linear hardware model that incorporates OS-reported metrics about CPU, memory, disk, and network utilization for each machine type and compared the power predictions from these models against homogeneous clusters of each machine type. Ultimately, this software-based modeling method seems to give accurate results only when the type of workload being predicted very closely matches the training workload on which the model was based. Additionally, I modeled the performance of heterogeneous clusters acting as a load-balanced web server and found that average response time is easily and accurately modeled based on single-machine runs for each hardware type in the cluster.

I also presented a Cluster Visualizer GUI for comparing potential clusters consisting of different types of machines. These imaginary clusters can be created without any restrictions or can be constrained based on a power envelope or on a limit of the monetary cost of the hardware. Two clusters can be compared side-by-side based on power use at different levels of resource utilization, traditional performance numbers, power efficiency based on operations per Watt, or average response times when acting as a web server. All numbers in the visualizer come from the benchmarks I ran and were verified against scaled-up cluster runs of the same benchmarks and thus are representative of real performance and power

achievable within a homogeneous cluster. This visualizer makes it easier to compare new sets of hardware to traditional servers along different axes to see if the alternative hardware can obtain the same level of service previously offered by the servers.

9 Acknowledgements

This project could not have been seen to completion without the assistance and support of numerous individuals and groups. Thanks to Randy H. Katz for direction and guidance on this project and to David Culler for his valuable input. Many thanks to the indispensable Albert Goto and Jon Kuroda for their fast, effective help in getting systems up and keeping them running. Further thanks go out to Stephen Dawson-Haggerty for his help in dealing with various power meters, to Yanpei Chen for initially laying the groundwork for investigating power-efficiency in Hadoop, to John Davis and Suzanne Rivoire for their part in the initial cluster comparison and modeling work, and to Ken Lutz and the SIGCluster group for their efforts in creating an energy-proportional cluster on which to conduct research. Final thanks to all the LoCal-ers and others who gave feedback and encouragement along the way. This work was made possible by a fellowship from NDSEG.

References

- [1] D. Andersen, J. Franklin, et al., “FAWN: a fast array of wimpy nodes,” in *Proc. of the 22nd ACM Symp. on Operating Systems Principles (SOSP)*, Big Sky, MT, Oct. 2009.
- [2] L.A. Barroso, U. Hoelzle, “The case for energy-proportional computing,” *IEEE Computer*, vol. 40, no. 12, Dec. 2007, pp. 33-37.
- [3] Y. Chen, L. Keys, R. Katz, “Towards Energy Efficient MapReduce,” Technical report, University of California at Berkeley, August 2009.
- [4] D. Economou, S. Rivoire, et al., “Full-system power analysis and modeling for server environments,” in *Proceedings of the Workshop on Modeling, Benchmarking, and Simulation (MoBS)*, June 2006.
- [5] R. Guerra, J. Leite, G. Fohler, “Attaining Soft Real-Time Constraint and Energy-Efficiency in Web Servers,” in *ACM Symposium on Applied Computing (SAC)*, 2008.

- [6] J. Hamilton, "CEMS: low-cost, low-power servers for internet-scale services," in *Proc. of the 4th Biennial Conference on Innovative Data Systems Research (CIDR)*, Asilomar, CA, Jan. 2009.
- [7] T. Heath, B. Diniz, et al., "Energy conservation in heterogeneous server clusters," in *Proceedings of the Symposium on Principles and Practice of Parallel Programming (PPoPP)*, June 2005.
- [8] C. Isci and M. Martonosi, "Runtime power monitoring in high-end processors: Methodology and empirical data," in *Proc. of the International Symposium on Microarchitecture (MICRO-36)*, Dec. 2003.
- [9] R. Joseph and M. Martonosi, "Run-time power estimation in high performance microprocessors," in *Proc. of the International Symposium on Low-Power Electronics and Design (ISLPED)*, Aug. 2001.
- [10] I. Kadayif, T. Chinoda, et al., "vEC: Virtual energy counters," in *Proc. of the ACM SIGPLAN/SIGSOFT Workshop on Program Analysis for Software Tools and Engineering (PASTE)*, June 2001.
- [11] L. Keys, S. Rivoire, J. Davis, "The Search for Energy Efficient Cluster Building Blocks", in *Workshop on Energy Efficient Design (WEED)*, Saint-Malo, France, June 2010.
- [12] A. Krioukov, P. Mohan, S. Alspaugh, L. Keys, D. Culler, R. Katz, "NapSAC: Design and Implementation of a Power Proportional Web Server Cluster," in *First ACM SIGCOMM Workshop on Green Networking*, New Delhi, India, August 2010.
- [13] J. Leverich and C. Kozyrakis, "On the energy (in)efficiency of Hadoop clusters," in *Proc. of the 2nd Workshop on Power-Aware Computing and Systems (HotPower)*, Big Sky, MT, Oct. 2009.
- [14] K. Lim, P. Ranganathan, et al., "Understanding and designing new server architectures for emerging warehouse-computing environments," in *Proc. of the 35th Intl. Symp. on Computer Architecture (ISCA)*, Beijing, China, June 2008.
- [15] V.J. Reddi, B. Lee, et al., "Web search using small cores: quantifying the price of efficiency," Microsoft Research Technical Report MSR-TR-2009-105, Aug. 2009.
- [16] S. Rivoire, "A Comparison of High-Level Full-System Power Models," in *Proc. of the 1st Workshop on Power-Aware Computing and Systems (HotPower)*, 2008.

- [17] S. Rivoire, M.A. Shah, P. Ranganathan, C. Kozyrakis, “JouleSort: A Balanced Energy-Efficiency Benchmark,” in *ACM SIGMOD*, Beijing, China, June 2007.
- [18] US Environmental Protection Agency (EPA), ENERGY STAR Program, “Report to Congress on Server and Data Center Energy Efficiency”, Public Law 109-431, August 2007.

10 Appendix

The hardware presented in the cluster is easily configurable, and new machine types can be easily added through the included Python script.

The inputs to the CV are a .profile CSV for each type of hardware available. Each line in the .profile for a piece of hardware is preceded by a tag for its associated benchmark. The following formats are used for each benchmark or other information:

SpecPower

```
cpu:<utilization>,<number of operations>,<power>,<operations per Watt>
```

Web Server

```
web:<rate>,<resp time>
```

Number of machines of this hardware type

```
total machines=<number machines>
```

Hardware Cost

```
cost=<amount>
```

To obtain results for SpecPower entries, you should collect power measurements while you run the included SpecPower **run-all** script on a machine of the new hardware type you would like to add. After the run is complete, you will need to locate the Results folder and find the `ssj-*-raw` file. Save that somewhere handy, along with the file where you collected all the power measurements.

Web server entries can be obtained by running the included autobench script. In the autobench script, you should set the command line option “`-file=;filename;`” to a file name of your choice. Save that file somewhere handy after the run is complete.

After running the SpecPower and autobench tests, you should run the **create-profile.py** script and then input the locations of the necessary files when asked for them. The script

will parse your files and add them to the new hardware .profile, which will be used the next time you open the CV GUI.