

# Power-efficient Server-class Performance from Arrays of Laptop Disks

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## Abstract

The disk array of a server-class system can account for a significant portion of the server's total power budget. Moreover many data centers now find themselves power-limited: unable to expand capacity without investing in new electric service or air conditioning equipment, both of which have very large incremental costs.

State-of-the-art laptop disks have response times and bandwidths within a factor of 2.5 of their server class cousins, and consume less than one sixth the energy. These ratios suggest the possibility of replacing a server-class disk array with a larger array of mirrored laptop disks. By spinning up a subset of the disks proportional to the current workload, we can exploit the latency tolerance and parallelism of typical server workloads to achieve significant energy savings, with equal or better peak bandwidth. Potential savings range from 50% to 80% of the total disk energy consumption. Conversely, if disks account for half of a data center's current energy usage, we may realize an increase of 25% to 40% in computational and storage capacity without an increase in power or cooling requirements.

# 1 Introduction

Data centers capable of providing Internet, application, database and network services are an increasingly important component of the world's computing infrastructure. In 1995 there were 20,000 servers in the world. As of June 2001, that number had reached six million [Maximum Throughput Inc, 2002]. Most existing research on data center design has aimed to improve performance, reliability and availability. Recently, however, researchers have begun to recognize the importance of energy efficiency [Chase and Doyle, 2001; Bohrer *et al.*, 2002]. Scientists at the Lawrence Berkeley National Laboratory have estimated that the annual energy used by servers, minicomputers, and mainframes exceeded 19 terawatt-hours (TWh) in 1999 [Kawamoto *et al.*, 2000] (equivalent to the total output of four large commercial power plants). Moreover, the increase in demand for data center services suggests that by 2005 new data centers will require approximately 40TWh or \$4B at \$100 per MWh unless they become more energy efficient [Chase and Doyle, 2001].

Increased data center power consumption translates directly into higher total cost of ownership, attributable to operating power, cooling, and decreased reliability. Over the ten year life cycle of a typical data center, cooling and power equipment accounts for 8% and 36% respectively of the total cost of ownership, while the electricity cost is at the order of 19% [Rasmussen]. Hence, power consumption related costs can account for 63% of the total cost of ownership. Moreover many data centers now find themselves power-limited: unable to expand capacity without investing in new electric service or air conditioning equipment, both of which have very large incremental costs. In addition, since data centers have limited power densities (at the order of  $30 W/ft^2$  on average [Rasmussen]) expansion may require renting additional space just for the purpose of accommodating the increased power consumption, increasing significantly the rental cost. In such cases, power efficiency can become a major parameter in the design of a data center: expanding the data center with power efficient equipment may be an attractive solution even if it is associated with a higher capital investment. Our work suggests a power-efficient storage system design based on *currently available* disk technology.

A recent white paper suggests that disk drives in a data center can account for 27% of total electric consumption [Maximum Throughput Inc, 2002]. In some configurations the fraction can be significantly higher. A Dell PowerEdge 6650 [DELL Inc., 2003], for example, comes equipped with 4 Intel Xeon 2.0 GHz processors and 292 15 KRPM hard drives. The processors are rated at 58W each, while an operational SEAGATE ST318453 15KRPM 18GB server-class disk drive consumes 15W [Seagate, 2003]. In such a configuration the hard disks consume  $15\times$  more power than the processors. If we assume, conservatively, that disks account for 50% of the power consumption of a large data center, then a 50% savings in disk power may translate into a 25% increase in data center size with no additional cooling or electrical service requirements.

Previous work on the energy efficiency of storage systems has focused largely on the hard drives used in mobile devices. Such drives support multiple non-operational low power modes that can provide significant energy savings during relatively long periods of inactivity (on the order of tens of seconds). The key idea in this work is to place the hard drive into a non-operating low power mode during relatively long periods of inactivity [Douglis *et al.*, 1995; Douglis *et al.*, 1994; Helmbold *et al.*, 1996; Li *et al.*, 1994]. Unfortunately, such policies do not transfer in an obvious way to the server environment. Server-class disks require tens of seconds to move from an inactive to an active state, and consume tens of Watts while "spinning up". In order to save energy by spinning down, they must be idle for significantly longer than their laptop-class counterparts. At the same time, server workloads are characterized by disk access patterns that have significantly shorter request inter-arrival times than are typical in mobile workloads. Finally, server-class disks are not designed for frequent stop-start cycles; heavy use of standby mode can be

expected to significantly lower their mean time to failure.

To improve the energy efficiency of server-class storage systems Gurusurthi et al. have suggested the use of DRPM [Gurusurthi *et al.*, 2003], an approach that dynamically modulates disk speed depending on current workload, decreasing the power required to keep the platters spinning when the load is light. Given the load fluctuations typical of web and transaction processing [Bohrer *et al.*, 2002], such an approach can save significant amounts of energy during periods of low activity while maintaining adequate response times during peaks. Unfortunately, DRPM disks are not yet commercially available. As an alternative, we suggest replacing each server-class disk in an array with a small number (three seems right, given current technology) of mirrored, energy-efficient laptop-class disks. Carrera et al. [Carrera *et al.*, 2003] briefly consider this possibility, but dismiss it based on a four-to-one replacement rate, previous generation power-consumption numbers, and no consideration of spin-down. With more recent numbers (which seem to be moving in the “right” direction), a three-disk array of today’s 2.5-inch devices can be expected to consume only 50% of the power of a high-end SCSI disk, while providing comparable or even higher throughput under heavy load, by exploiting read parallelism. Substantially larger power savings may be achieved when the load is light, by spinning down disks that represent excess capacity.

The rest of the paper is structured as follows. Section 2 describes the characteristics of laptop and server-class disks and makes the case for using the former in server disk arrays. Section 3 describes an array of laptop disks designed to minimize energy consumption. Section 4 shows the energy efficiency potential of the proposed design. Finally, section 5 describes related work and section 6 presents our conclusions.

## 2 Disk Arrays: Laptop or Server-class Disks?

The constant need of data-centric services for higher throughput and shorter response times is driving server-class hard drives toward higher rotational speeds and shorter seek latencies. State-of-the-art server class disks have rotational speeds of 15K RPM and seek times shorter than 4ms. As shown in Table 1, such performance characteristics come at the cost of significantly increased power budgets. Even when idle, a 15 KRPM hard drive consumes more than 12 Watts.

In comparison to their server-class counterparts, modern hard disks for mobile systems have worse performance characteristics. However, the need of the mobile market for longer battery lifetimes makes energy efficiency a compelling design goal. Even when active, modern laptop hard drives typically consume less than 3 Watts. They also typically support several non-operational low power modes (Table 1): Active Idle, Low Power Idle, Standby and Sleep.<sup>1</sup> Non-operational low power modes can save significant energy during periods of disk inactivity.

A comparison of the hard disks parameters presented in Table 1 shows that a modern 7200 RPM laptop hard disk, such as the Hitachi TravelStar 7K60, has the same cache size as, and similar capacity to, a 15 KRPM server-class disk. The server-class disks provide about  $2\times$  better bandwidth and  $2.5\times$  better latency, but consume  $6\times$  as much power, even when the low power modes of the laptop disk are not being used. Such differences suggest that by replacing each high performance disk in a server environment with a mirrored (RAID Level 1) array [Patterson *et al.*, 1988] of several laptop-class hard disks (Table 1 suggests a replacement ratio of 3), one can achieve similar or higher I/O throughput at significantly lower power. Individual request response times will be higher, but for most large secondary storage systems aggregate I/O throughput is (within limits) more important [Chen *et al.*, 1994].

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<sup>1</sup>In the Active Idle state the head servoing mechanism and portion of the electronics are off. In the Low Power Idle state the disk is still spinning, but the electronics may be partially unpowered, and the heads may be parked or unloaded. In the Standby state the disk is spun down. The Sleep state powers off all remaining electronics; a soft reset is required to return to higher states.

Disk	DK23DA-F30	TravelStar 7K60	UltraStar 15K73	Cheetah 15K.3
Price	\$127	\$210	\$195	\$199
Capacity	30GB	60GB	73.9GB	73GB
Form Factor	2.5inch	2.5inch	3.5inch	3.5inch
Cache Size	2048KB	8192KB	8192KB	8192KB
Rotational Speed	4200RPM	7200RPM	15037RPM	15000RPM
Max. Transfer Rate	35MB/s	64MB/sec	129MB/s	112MB/s
Avg. Seek Time	13ms	10ms	3.9ms	3.8ms
Max. Seek Time	25ms	16ms	7.2ms	6.7ms
Operating Shock	180G/2ms	200G/2ms	15G/11ms	60G/2ms
Recording Density	600KBPI	624KBPI	N/A	533KBPI
Track Density	55.0KTPI	88.2KTPI	N/A	64KTPI
Avg. Active Power	2.1W	2.5W	15.6W	14.9W
Performance Idle	1.6W	2W	12.0W	12.2W
Active Idle	N/A	1.3W	N/A	N/A
Low Power Idle	0.6W	0.85W	N/A	N/A
Standby	0.25W	0.25W	N/A	N/A
Sleep	0.1W	0.1W	N/A	N/A
Standby to Ready	3sec	3sec	25sec	20sec

Table 1: Characteristics of four mobile and server-class hard drives. Hitachi *DK23DA-F30* [Hitachi Global Storage Technologies, 2001] is a 2001 mobile hard drive, Hitachi *TravelStar 7K60* [Hitachi Global Storage Technologies, 2003a] is the newest mobile hard drive implemented by the Hitachi Global Storage Technologies and the first mobile hard drive with a rotational speed of 7200 RPM. Hitachi *UltraStar 15K73* [Hitachi Global Storage Technologies, 2003b] and Seagate *Cheetah 15K.3* [Seagate, 2003] represent modern server-class drives. The prices presented were the lowest prices retrieved from <http://www.pricegrabber.com> on April 22, 2004. The rest of the parameters have been taken from the respective hard drive specifications. The Transfer rate represents the maximum media-to-buffer transfer rate. For the two mobile drives the row “Standby to Ready” represents the time to transition from the standby low power mode (heads are parked and platters are spun down) to ready (performance idle mode), while for the server-class disks the time from power on to ready.

The lower power consumption of laptop hard drives has additional advantages. First, it can lead to improved reliability. Increased temperatures caused by heat dissipation in densely packed storage systems can lead to component malfunctions: for every degree that the operating temperature of a hard disk exceeds the recommended level the failure rate increases two to three percent [Maximum Throughput Inc, 2002]. Over time, a hard disk operating at just five degrees above its recommended temperature is 10 to 15 percent more likely to fail. The resistance of laptop disks to operating shocks (Table 1) also increases their reliability. Second, reduced power consumption can lead to a smaller cost for cooling equipment. Third, the smaller form factor, combined with lower heat dissipation, means that several (certainly three) laptop disks can be squeezed into the same physical space as their server-class counterpart, while generating much less acoustic noise.

We believe that the attractiveness of laptop hard drives as an alternative to server-class disks will increase over time. The notebook market is growing faster than the desktop and server markets. Rising demand, together with the trend toward higher performance mobile processors, operating systems, interfaces, and buses, is fueling the development of ever faster laptop hard drives. Recent technological advancements,

such as adaptive formatting [Laroia and Condon, 2003], antiferromagnetically-coupled (AFC) media [International Business Machine Corporation (IBM), 2001], fluid dynamic motors [Blount, 2001], and fempto sliders [Best *et al.*, 2003], have led to faster, more reliable, higher capacity laptop hard drives at (almost) the same power budget. The 2004 TravelStar 7K60 hard drive, when compared to the 2001 Hitachi DK23DA laptop hard drive (Table 1), has twice the capacity,  $1.7\times$  the rotational speed, and improved seek times, while its power consumption has increased by only 25%. The same technologies that have led to the development of the 7K60 promise additional future improvements. For example the antiferromagnetically-coupled media [Laroia and Condon, 2003] and the fempto slider [Best *et al.*, 2003] suggest future areal densities of  $100\text{Gbit}/\text{inch}^2$ , compared to roughly  $70\text{Gbit}/\text{inch}^2$  for current commercial products.

The above trends make arrays of laptop disks an increasingly attractive alternative to high performance server class disks. The principal disadvantage of such an array is its price: with laptop and server-class disks of comparable capacity costing roughly the same amount (Table 1), replacing each server-class disk with several laptop disks will increase the initial investment several fold. However, such an investment may be justified when data center expansion is blocked by limited power density or the high incremental cost of new power and cooling capacity. The initial investment will also be partially offset by reduced electric bills and capital spent on cooling and power equipment. In addition, the redundancy of mirroring should reduce the need for parity disks, allowing an array of  $n + 1$  server-class disks to be replaced by roughly  $3n$  laptop disks, rather than  $3n + 3$ , where  $n$  is the parity width. (Striping may still be desirable for high bandwidth sequential reads.) Finally, economies of scale suggest that laptop disk prices may improve faster than those of server-class disks.

### 3 Design Issues in an Array of Laptop Disks

The idea of using arrays of laptop disks in place of server-class disks has as a goal to minimize power consumption while maintaining acceptable aggregate I/O throughput. Based on the discussion in section 2, replacing each server-class disk in a large scale storage system with a mirrored array of three 7200 RPM laptop hard disks will provide similar or even better aggregate throughput at half the power budget, even if the disks remain active constantly. Additional power savings can be achieved by taking advantage of the varying workload intensity of web server systems and transaction processing systems [Bohrer *et al.*, 2002]. During low intensity periods, only the portion of the hard disks that is necessary in order to sustain acceptable throughput need actually be active. Depending on the exact characteristics of the workload, the additional disks may enter one of several low power modes. The choice of mode depends on the intensity of the workload and more specifically on the rate at which the secondary disks accept requests.

Traditional mirrored disk array systems aim to maximize aggregate throughput without regard to power consumption. Hence, common policies used to select the disk to service a request attempt to balance the load evenly across all mirrored disks. Examples of such policies include random selection, round-robin selection, or selection of the disk with the shortest request queue. Such load balancing schemes are inappropriate for power efficiency: the disk array controller may keep all disks active even during light workloads by spreading requests across the array.

A more power-friendly approach would be to use a policy that starts using secondary disks only when individual response times exceed a certain threshold. Such a policy has the advantage of increasing the request inter-arrival time to secondary disks, allowing them to drop into low power modes when the load is low. At the same time, by tracking the response times of individual requests and spinning up additional disks when those times exceed some acceptable threshold, we can guarantee not to damage aggregate throughput. A simple way to limit worst case response time is to track the number of pending requests in the queue of

State	Mobile Disk
Active	2.50 W
Performance Idle	2.00 W
Low Power Idle	0.85 W
Standby Power	0.25 W
Low Power Idle to Active Energy	1.45 J
Low Power Idle to Active Time	0.53 s
Active to Low Power Idle Energy	2.15 J
Active to Low Power Idle Time	0.85 s
Standby to Active Energy	9.00 J
Standby to Active Time	3.00 s
Active to Standby Energy	2.94 J
Active to Standby Time	1.25 s

Table 2: Abstract disk model parameters used calculate energy consumption. Values are based on the TravelStar 7K60 and UltraStar 15K73 disk.

each mirrored disk. New requests can be scheduled to one of the currently active disks until the number of requests in the queue exceeds a certain queuing threshold, at which point one of the secondary disks can be activated in order to service additional requests. If all disks in the system have exceeded their queuing threshold, a traditional load balancing scheme will become appropriate.

Unfortunately, while reads can be spread across disks, writes must be performed on all copies. This may lead to increased response times in write intensive workloads, since the aggregate write throughput is limited to that of a single disk. Power consumption may also increase with a decrease in the length of secondary disk idle intervals, which can lead to inefficient use of low power modes. Fortunately, Internet content delivery is characterized mostly by read activity. It may also be possible to reduce the power impact of writes (though not their performance impact) by updating only those disks that are currently active. Idle disks may be synchronized periodically using data from the primary disks or from a disk array write cache. We plan to explore such options in our future work.

Finally, in contrast to server disks, laptop disks are not designed for 100% duty cycles, which makes them less likely to perform well under continuous operational stresses [Anderson *et al.*, 2003]. Fortunately, the mirroring inherent in our design in combination with the ability to deactivate disks during periods of low load intensity can decrease the duty cycle of each disk in the mirrored array.

## 4 Energy Efficiency Potential of Laptop Disk Arrays

In this section we evaluate the idea of using laptop disk arrays in server-class storage systems. We conducted our experiments using the Disksim simulator [Ganger, 1995; Ganger *et al.*, 1999]. We augmented the simulator with code to model energy consumption. Part of the code is based on the Dempsey simulator [Zedlewski *et al.*, 2003]. The disk configuration parameters used in the simulations are based on the Hitachi TravelStar 7K60 and Hitachi UltraStar 15K73 disks (Table 1). In the simulations of the TravelStar 7K60 disk we assume a simplified disk power model with the characteristics shown in Table 2<sup>2</sup>.

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<sup>2</sup>We do not model the active idle power mode, since we do not have information about its transition time parameters. Our results are hence conservative, since the use of the active low power mode can provide additional savings even during short idle intervals. In addition, we do not model the Sleep mode.

Workload Type	Bandwidth (Rqs/sec)	Fraction of Max. <i>Srv</i> Bandwidth
<Exp-8>	124.73	78.75%
<Exp-10>	99.79	63.00%
<Exp-1000>	1.00	0.63%
<Par-10>	99.75	62.98%
<Par-50>	19.95	12.60%
Max. <i>Srv</i> Bandwidth	158.39	100.00%
Max. <i>Mbl</i> Bandwidth	211.66	133.63%

Table 3: Aggregate bandwidth in requests per second imposed by each workload tested and its fraction of the maximum bandwidth supported by the server-class disk (*Srv*). The maximum aggregate bandwidth of the laptop-disk array (*Mbl*) is also shown.

To capture the behavior of the proposed system under workloads with various degrees of intensity we conducted an open system simulation (i.e., one in which requests are assumed to be mutually independent) using synthetic workloads. In all the experiments, one million requests are issued. We use two types of distributions in order to model the inter-arrival time among requests generated by the synthetic workloads: an exponential distribution that leads to a “smoother” workload and a Pareto distribution that leads to a more “bursty” workload. We experiment with a wide range of mean inter-arrival times. In the remainder of the paper, we will follow the naming convention <*Distribution-Mean*> in order to refer to a specific workload. For example <Exp-10> represents a workload with request inter-arrival times that follow an exponential distribution with a mean of 10 *ms*, while <Par-50> represents a workload with request inter-arrival times that follow a Pareto distribution with a mean of 50 *ms*. Table 3 presents the aggregate bandwidth in requests per second imposed by each workload to the storage system. Similar workload configuration parameters were used in the evaluation of the DRPM approach [Gurumurthi *et al.*, 2003].

Across all experiments we present results for five systems. *Srv* represents a storage system consisting of a single server-class disk. The remaining four systems are variations of the laptop disk based array. We experiment with four different policies for selecting which disk among the replicas in the array should service a given request. The first disk selection policy, *Mbl-Balanced*, represents a traditional load balancing scheme that selects the disk in the array with the shortest queue. The remaining three policies represent the more power-conscious disk selection policy discussed in Section 3 with various queuing thresholds. The queuing threshold is 5 in the *Mbl-E5* system, 10 in the *Mbl-E10* system and 30 in the *Mbl-E30* system. The disk selection policy represents a tradeoff between energy efficiency and worst case response time for individual requests. Depending on the worst case response time that a server system can tolerate, we can use a traditional load balancing scheme in the array in order to achieve better performance or a power-conscious disk selection policy with a higher queuing threshold to achieve a more power efficient system.

Our first set of experiments evaluates the performance of the traditional and laptop-disk systems under two intensive read-only workloads, <Exp-8> and <Exp-10>. Figures 1 and 2 present the results. Since the laptop disk array is able to support a higher maximum aggregate throughput than the server-class disk (212 versus 159 requests per second), the *Mbl-Balanced* system slightly outperforms the server-class disk during the most intensive <Exp-8> workload (Figure 1). It leads to an average response time of 17 *ms*, versus 20 *ms* for the server disk. The power-conscious arrays exhibit worse response times. Larger queuing thresholds lead to larger queuing delays for a significant portion of the requests and hence a larger average response time. Across all experiments, however, response time remains below half a second, a reasonable worst-case value for a web server or similar system. Results for the <Exp-10> distribution are similar. The main difference is that the server-class disk performs slightly better than the balanced disk array. Since

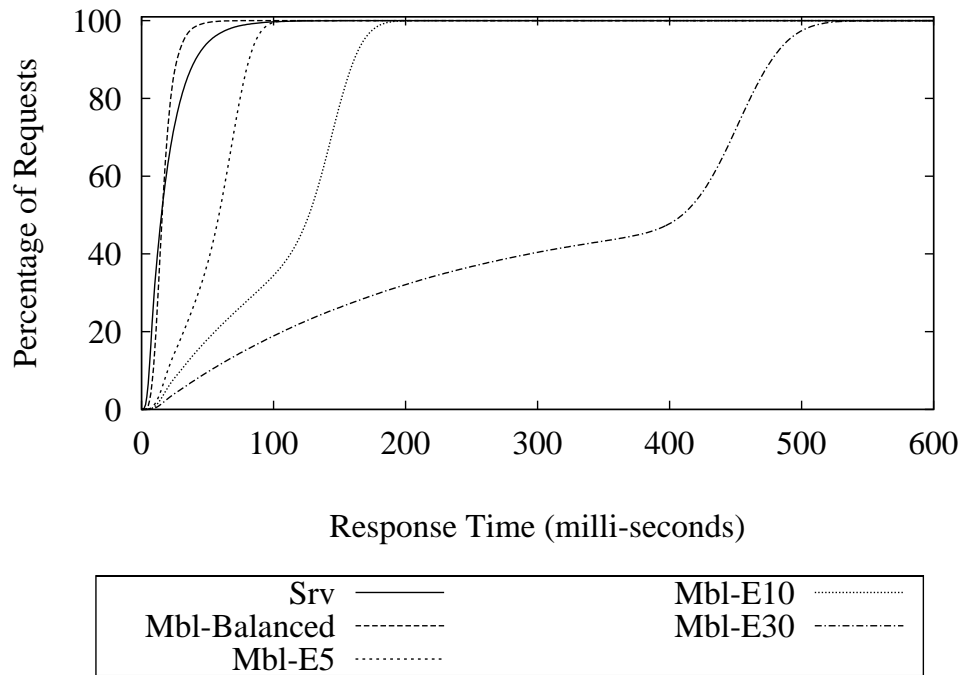


Figure 1: Cumulative request response time distribution for the read-only <Exp-8> workload. Higher queuing delays in the *Srv* system lead to slightly worse response times than in the *Mbl-Balanced* system.

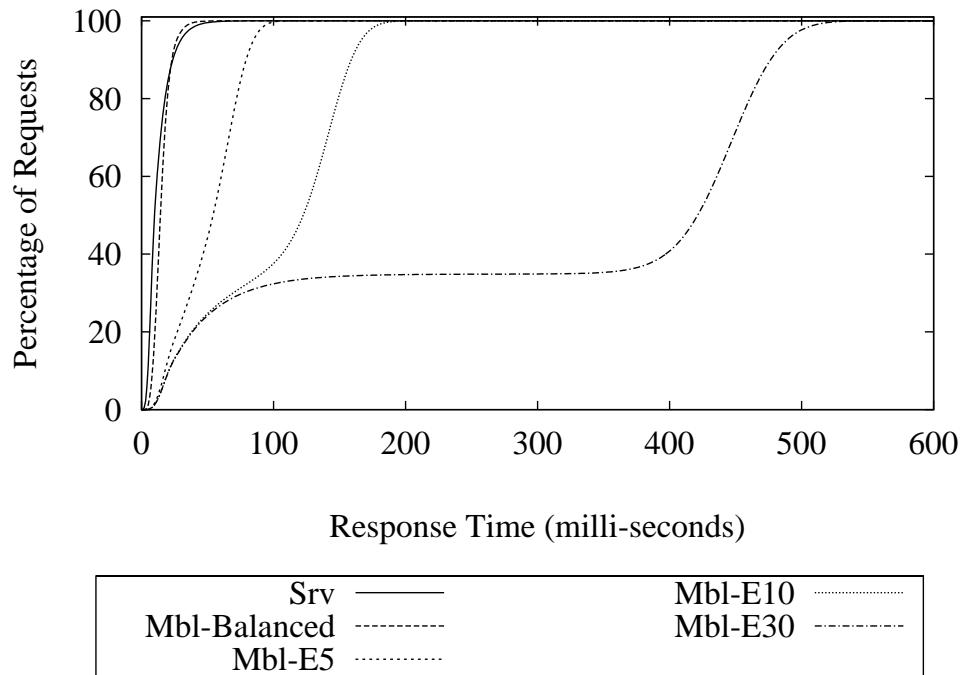


Figure 2: Cumulative request response time distribution for the read-only <Exp-10> workload.



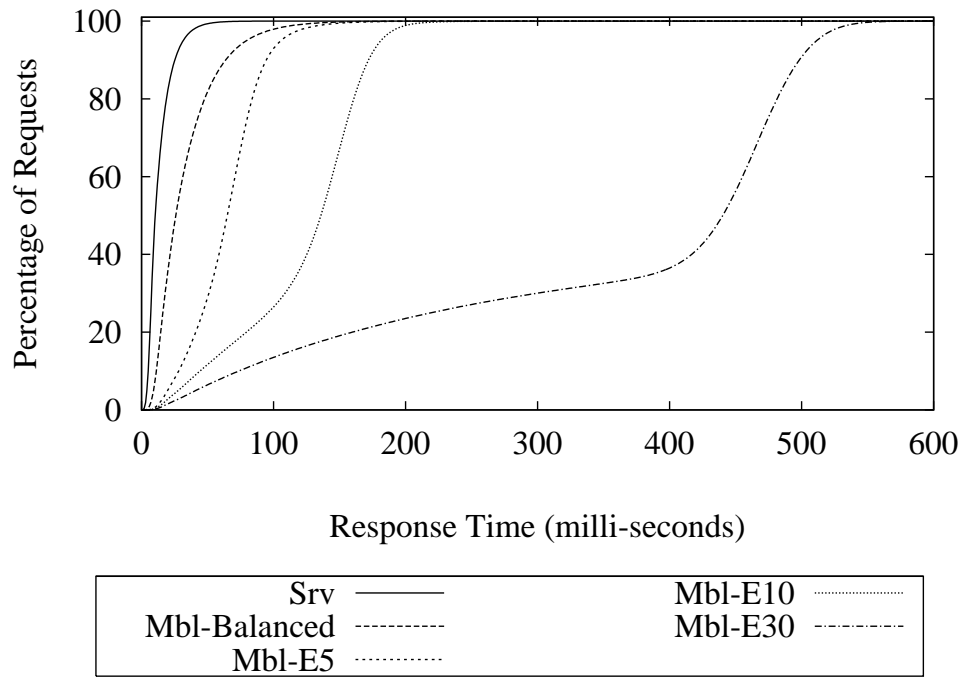


Figure 4: Cumulative request response time distribution for the <Exp-10> workload. 20% of the requests are writes.

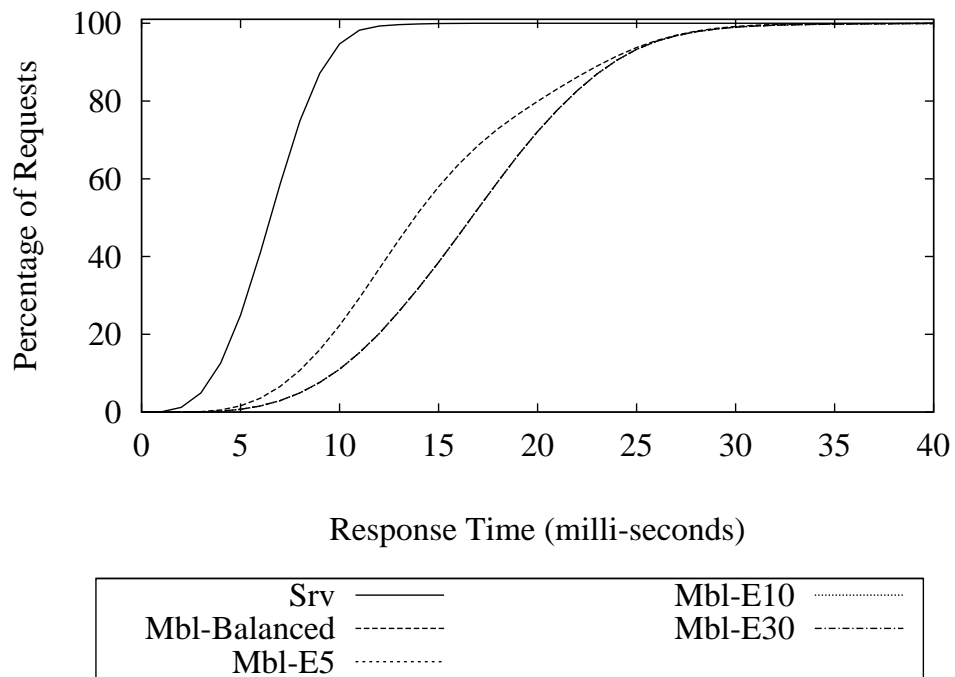


Figure 5: Cumulative request response time distribution for <Exp-1000> workload. 20% of the requests are writes.

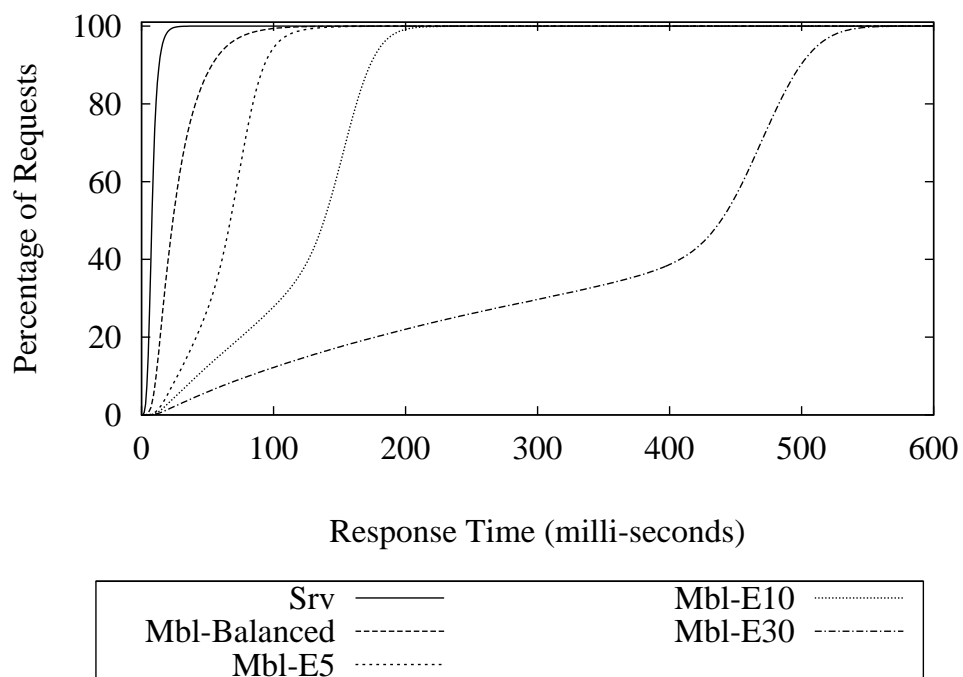


Figure 6: Cumulative request response time distribution for the <Par-10> workload. 20% of the requests are writes.

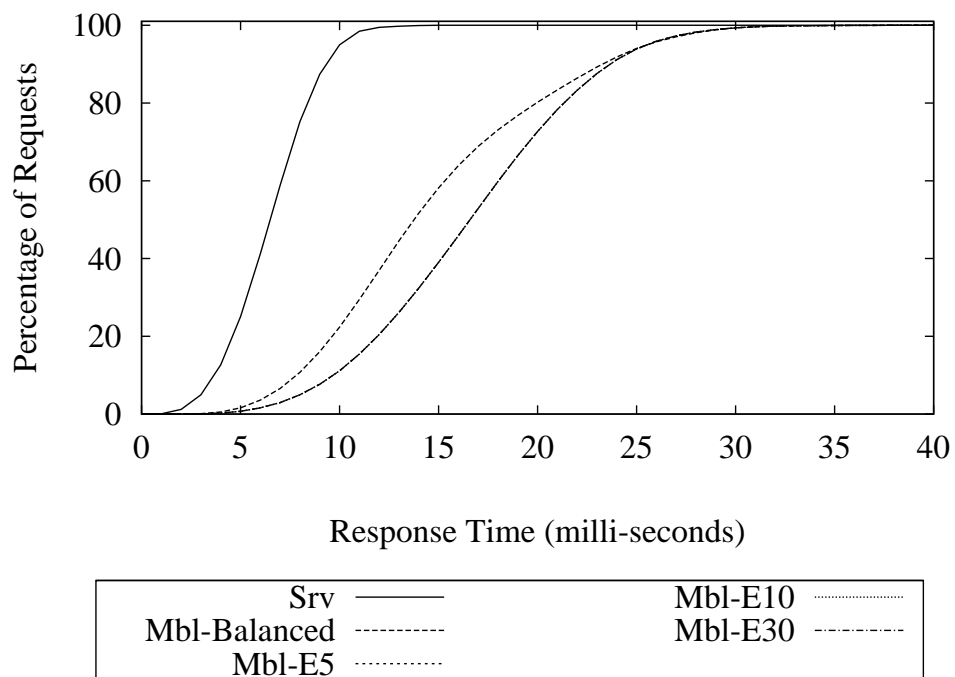


Figure 7: Cumulative request response time distribution for the <Par-50> workload. 20% of the requests are writes.

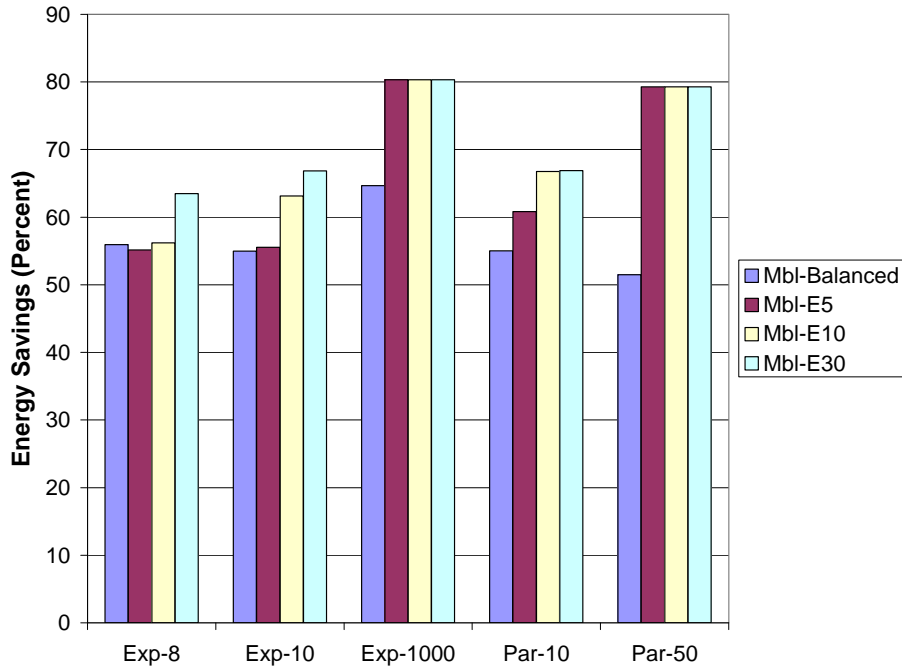


Figure 8: Energy Savings of the array of laptop disks during read-only workloads. The base case for the comparison is the energy consumption of the server-class disk for the respective workloads.

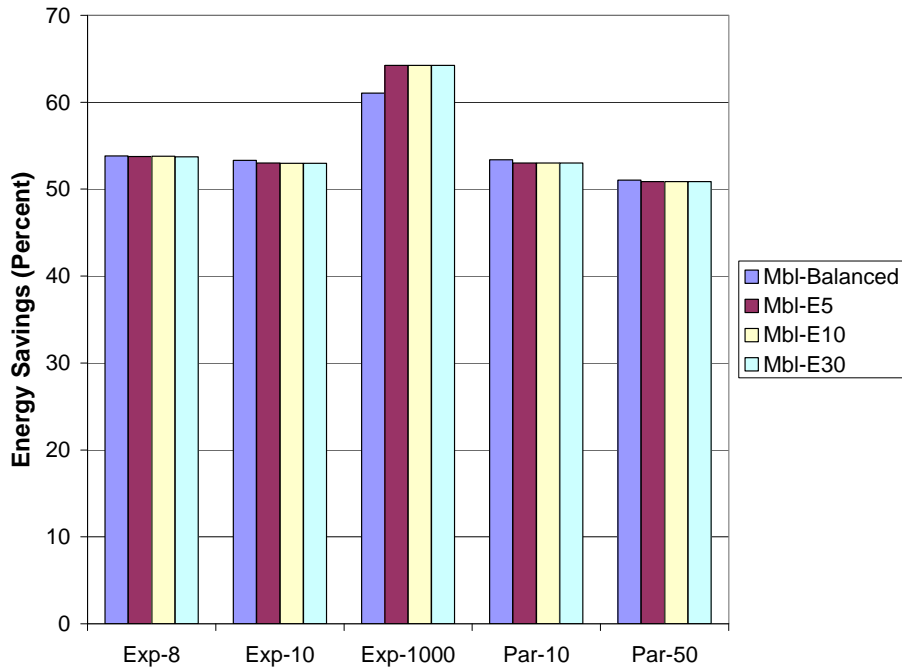


Figure 9: Energy Savings of the array of laptop disks during workloads with 20% write requests. The base case for the comparison is the energy consumption of the server-class disk for the respective workloads.

## 5 Related Work

**Power Management for Mobile Systems.** The research community has been very active in the area of power-conscious systems during the last few years. Ellis et al. [Ellis, 1999] emphasized the importance of energy efficiency as a primary metric in the design of operating systems. ECOSystem [Zeng *et al.*, 2002] provides a model to account for and allocate the available energy among competing applications according to user preferences. Odyssey [Flinn and Satyanarayanan, 1999; Noble *et al.*, 1997] provides operating system support for application-aware resource management. Several policies have been proposed for decreasing the power consumption of processors that support dynamic voltage and frequency scaling. The key idea is to schedule so as to “squeeze out the idle time” in rate-based applications. Several researchers have proposed voltage schedulers for general purpose systems [Flautner and Mudge, 2002; Govil *et al.*, 1995; Weiser *et al.*, 1994; Pering *et al.*, 2000].

**Power Management for Server Systems.** The importance of power management in server systems has been noted by several researchers [Bohrer *et al.*, 2001; Bohrer *et al.*, 2002; Chase and Doyle, 2001]. Bohrer et al. [Bohrer *et al.*, 2002] explore the potential of dynamic voltage scaling for power savings in web servers, while Elnozahy et al. [Elnozahy *et al.*, 2003] suggest the combination of dynamic voltage scaling with “request batching”, a technique that groups requests and executes them in batches, to reduce the processor power consumption of web servers. Pinheiro et al. [Pinheiro *et al.*, 2001] propose turning machines on and off in server clusters in order to reduce energy consumption. Chase et al. [Chase *et al.*, 2001] explore a similar idea and introduce an economic approach to resource management by allowing web servers to “bid” for resources.

**Power Management for Storage Systems.** The cost and risks of standby mode played a factor in the early investigation of hard-disk spin-down policies [Douglass *et al.*, 1995; Douglass *et al.*, 1994; Helmbold *et al.*, 1996; Li *et al.*, 1994] for mobile systems. Unfortunately such spin-down policies are not effective in server-class storage systems. Server-class disks are not designed for rapid spin-down and spin-up, and server workloads typically have access patterns with very short idle intervals, which would limit the utility of low-power modes even if they were available.

Recently, several groups have begun to investigate the deliberate generation of *bursty* access patterns that provide more opportunities for the hard disk to transition to a low power mode. Heath et al. [Heath *et al.*, 2002] and Weissel et al. [Weissel *et al.*, 2002] have proposed user-level mechanisms to increase the burstiness of I/O requests from individual applications. Papathanasiou et al. [Papathanasiou and Scott, 2003; Papathanasiou and Scott, 2004] explore operating system prefetching and caching techniques to “shape” the disk access pattern of the system as a whole. We believe that such techniques, though initially intended for mobile systems, could improve the efficiency of servers as well.

Colarelli et al. [Colarelli and Grunwald, 2002] explore massive arrays of idle disks, or MAID, as an alternative to conventional mass storage systems for scientific computing; they demonstrate performance comparable to that of a conventional RAID system at significantly lower power. Gurumurthi et al. [Gurumurthi *et al.*, 2003] suggest the use of DRPM [Gurumurthi *et al.*, 2003], an approach that dynamically modulates disk speed depending on current workload, decreasing the power required to keep the platters spinning when the load is light. Carrera et al. [Carrera *et al.*, 2003] compare various design schemes for conserving disk energy in network servers, including schemes based on laptop and DRPM disks. While they confirm the energy savings possible with DRPM, the older generation laptop disks used in their study, combined with conservative assumptions regarding redundancy, lead to the conclusion that replacing server disks with multiple laptop disks will not lead to similar savings. Technological trends, however, are narrowing the performance gap between laptop- and server-class disks, while widening the power gap. Put another way, high-performance disks, like high-performance processors, are edging farther and farther past

the point of diminishing returns. This, combined with the fact that multi-speed hard disk drives are not yet commercially available, suggests that laptop-class disk arrays are indeed a practical alternative.

Pinheiro et al. [Pinheiro and Bianchini, 2004] explore a technique called popular data concentration (PDC) that migrates frequently accessed data to a subset of the disks in an array. The goal is to skew the load toward a subset of the disks so that others can drop into low-power modes. Finally, Zhu et al. [Zhu et al., 2004] propose several power-aware storage cache management algorithms that provide additional opportunities for a disk power management system to save energy. Such algorithms might work well in conjunction with mirrored laptop disks, leading to higher energy efficiency than could be achieved with either approach alone.

## 6 Conclusions

Given the increasing importance of power management in server farms and the rapid pace of technological improvement in small form factor hard disks, we have raised the possibility of replacing an array of server-class disks with a larger array of laptop-class (2.5”) disks. Current technological design points suggest a replacement ratio of three to one.

The principal disadvantage of a laptop disk array is its initial cost. A secondary disadvantage is higher latency for individual requests when the load is light. Potential advantages include significantly lower operational power, lower cooling needs, potentially denser packaging, lower noise, potentially higher peak bandwidth, potentially higher mean time to data loss (due to mirroring), and the opportunity to ride the faster development curve for commodity laptop disks. Back-of-the-envelope calculations (confirmed by simulations) suggest a baseline power savings of 50% when all laptop disks are active. Simulations confirm that significant additional savings, up to 80%, can be achieved when the load is light by exploiting the non-operational low-power modes supported by laptop disks. Under high load, simulations also indicate a modest *improvement* in average latency, as requests that would queue for a single server-class disk are serviced by separate laptop disks.

Many questions remain for future work. The relative costs of replacing failed drives in conventional and laptop-array based storage systems will depend not only on the MTTF of various devices, but on the extent to which MTTF itself depends on thermal management. More definitive evaluation will require not only the use of actual devices (rather than simulations), but also the development of realistic on-line power management policies (the optimal policy assumed in our simulations is not feasible in practice).

As mentioned in Section 3, we plan to consider policies in which writes are flushed only to drives that are currently spinning. Such policies obviously have an impact not only on energy and performance, but on failure resilience as well. The mirroring inherent in our proposal effectively introduces an extra dimension in the RAID design space; we will want to consider the interaction between our mirroring and both routine and recovery-mode file striping. We also plan to consider the staging of writes in non-volatile solid-state cache.

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