Towards Higher Disk Head Utilization: Extracting "Free" Bandwidth From Busy Disk Drives

Christopher R. Lumb, Jiri Schindler, Gregory R. Ganger,
Erik Riedel, David F. Nagle

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School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213

Abstract

Freeblock scheduling is a new approach to utilizing more of disks' potential media bandwidths. By filling rotational latency periods with useful media transfers, 20{50% of a never-idle disk's bandwidth can often be provided to background applications with no effect on foreground response times. This paper describes freeblock scheduling and demonstrates its value with two concrete applications: free segment cleaning and free data mining. Free segment cleaning often allows an LFS file system to maintain its ideal write performance when cleaning overheads would otherwise cause up to factor of 3 performance decreases. Free data mining can achieve 45 - 70 full disk scans per day on an active transaction processing system, with no effect on transaction performance.

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1 Introduction

Disk drives increasingly limit performance in many computer systems, creating complexity and restricting functionality. Interestingly, however, the rate of improvement in media bandwidth (40–60% per year) has kept pace with other computer system attributes that are driven by Moore's Law. It is only the mechanical positioning aspects (i.e., seek times and rotation speeds) that fail to keep pace. If 100% utilization of the potential media bandwidth could be realized, disk performance would scale in proportion to the rest of the system over time. Unfortunately, utilizations of 2–15% are more commonly observed in practice.

This paper describes, develops, and analyzes a new approach to increasing media bandwidth utilization called *freeblock scheduling*. By interleaving low priority disk activity with the normal workload (here referred to as background and foreground, respectively), one can replace many foreground rotational latency delays with useful background media transfers. With appropriate freeblock scheduling, background tasks can receive 20–50% of a disk's potential media bandwidth without any increase in foreground request service times. Thus, this background disk activity is completed "for free" in the context of mechanical positioning for foreground requests.

There are many disk-intensive background tasks that are designed to occur during otherwise idle time. Examples include disk reorganization, file system cleaning, back-up, prefetching, write-back, integrity checking, virus detection, tamper detection, report generation, and index reorganization. When idle time does not present itself, these tasks either compete with foreground tasks or are simply not completed. Further, when they do compete with other tasks, these background tasks do not take full advantage of their relatively loose time constraints and paucity of sequencing requirements. As a result, these "idle time" tasks often cause performance or functionality problems in busy systems. With freeblock scheduling, these background tasks can operate continuously and efficiently, even when they do not have the system to themselves.

This paper also quantifies the effects of disk, workload, and scheduling algorithms on potential free bandwidth. Algorithms are developed for increasing the available free bandwidth and for efficient freeblock scheduling. For example, with less than a 6% increase in

average foreground access time, a Shortest-Positioning-Time-First scheduling algorithm that favors reduction of seek time over rotational latency can provide an additional 66% of free bandwith. Experiments also show that, with proper data structures and algorithms, freeblock scheduling decisions can be made efficiently enough to be effective in systems with high load.

This paper demonstrates the value of freeblock scheduling with concrete examples of its use for storage system management and disk-intensive applications. The first example shows that cleaning in a log-structured file system can be done for free even when there is no truly idle time, resulting in up to a 300% speedup. The second example explores the use of free bandwidth for data mining on an active on-line transaction processing (OLTP) system, showing that over 47 full scans per day of a 9GB disk can be made with no impact on OLTP performance.

The remainder of this paper is organized as follows. Section 2 describes freeblock scheduling and discusses its use in systems. Section 3 quantifies the availability of potential free bandwidth and how it varies with disk characteristics, foreground workloads, and foreground disk scheduling algorithms. Section 4 describes our freeblock scheduling algorithm. Section 5 evaluates the use of free bandwidth for cleaning of LFS log segments. Section 6 evaluates the use of free bandwidth for data mining of active OLTP systems. Section 7 discusses related work. Section 8 summarizes the paper's contributions.

2 Free Bandwith

At a high-level, the time, T_{access}, required for a media access can be computed as

$$T_{access} = T_{seek} + T_{rotate} + T_{transfer}$$

Of T_{access}, only $T_{transfer}$ represents useful utilization of the disk head. Unfortunately, the other two components generally dominate. Many data placement and scheduling algorithms have been devised over the years to increase disk head utilization by increasing transfer sizes and reducing positioning overheads. Freeblock scheduling complements these techniques by transfering additional data during the time gap of T_{rotate}.

Fundamentally, the only time the disk head cannot be transferring data sectors to or from the media is during a seek. In fact, for most disks, the firmware will transfer a given requests' data to or from the media "out of order" to minimize wasted time; this feature is sometimes referred to as zero-latency or immediate access. While seeks are unavoidable costs associated with accessing desired data locations, rotational latency is simply an artifact of not being able to do something more useful with the disk head. The fact that disk platters rotate constantly means that a given sector will pass under the disk head at a given time, independent of what the disk drive is doing up until that time. So, there is an opportunity to do something more useful than just waiting for desired sectors to arrive at the disk head.

Free block scheduling consists of predicting how much rotational latency will occur before the next foreground media transfer, squeezing some additional media transfers into that time, and still getting to the destination track in time for the foreground transfer. The additional media transfers may be on the current or destination tracks, on another track near the two, or anywhere between them as illustrated in Figure 1. In the two latter cases, additional seek overheads will be involved, reducing the actual time available for the additional media transfers, but not completely eliminating it.

Accurately predicting future rotational latencies requires detailed knowledge of a disk's many performance attributes, including layout algorithms and time-dependent mechanical positioning overheads. These predictions can utilize the same basic algorithms and information that most modern disks employ for their internal scheduling decisions, which are based on overall positioning overheads (seek time plus rotational latency) [42, 24]. However, this may require that freeblock scheduling decisions be made by disk firmware. Fortunately, the increasing processing capabilities of disk drives [1, 26, 38] make advanced on-drive storage management feasible [46].

2.1 Using Free Bandwidth

Potential free bandwidth exists in the time gaps that would otherwise be rotational latency delays for foreground requests. Therefore, freeblock scheduling must opportunistically match these potential free bandwidth sources to real bandwidth needs that can be met within the given time gaps. The tasks that will achieve the largest fraction of potential free bandwidth

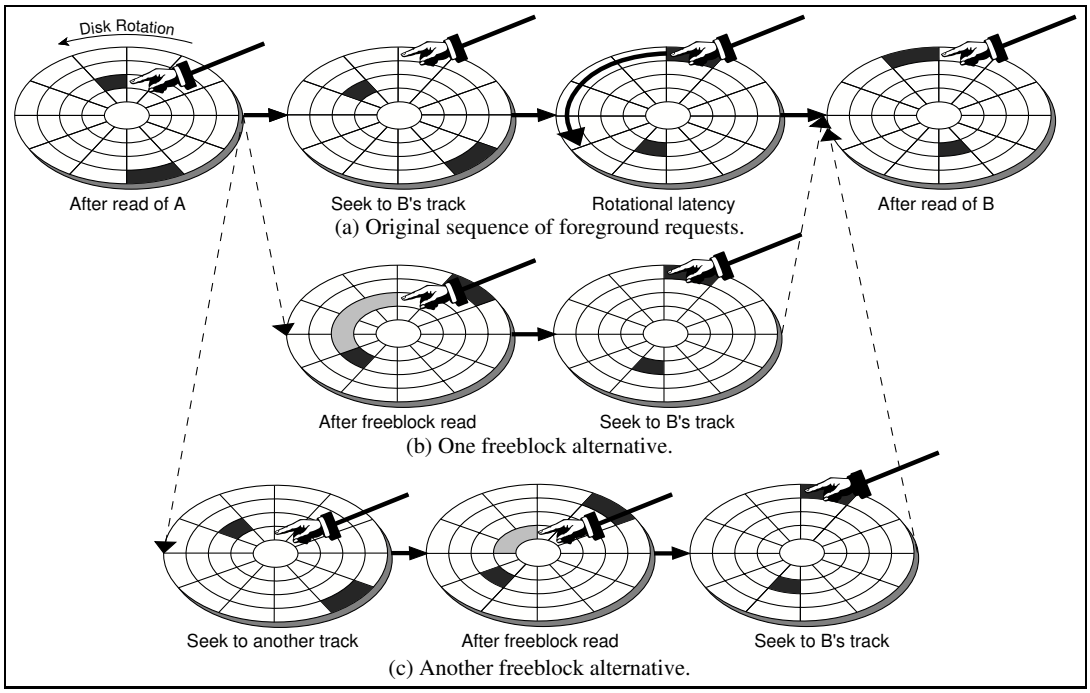


Figure 1: **Illustration of two freeblock scheduling possibilities.** Three sequences of steps are shown, each starting after completing the foreground request to block A and finishing after completing the foreground request to block B. Each step shows the position of the disk platter, the read/write head (shown by the pointer), and the two foreground requests (in black) after a partial rotation. The top row, labelled (a), shows the default sequence of disk head actions for serving block B, which includes 4 sectors worth of potential free bandwidth (a.k.a. rotatinal latency). The second row, labelled (b), shows free reading of 4 blocks on A's track using 100% of the potential free bandwidth The third row, labelled (c), shows free reading of 3 blocks on another track, yielding 75% of the potential free bandwidth.

are those that provide the freeblock scheduler with the most flexibility. Tasks that best fit the freeblock scheduling model have low priority, large sets of desired blocks, no particular order of access, and small working memory footprints.

Low priority. Free bandwidth is inherently in the background, and freeblock requests will only be serviced when opportunities arise. Therefore, response times may be extremely long for such requests. Further, for a set of equally important requests, freeblock scheduling is not appropriate. All such requests should be considered by the foreground scheduling algorithm, so as to minimize positioning delays and maximize disk head utilization. With proper foreground scheduling, any request scheduled within free bandwidth would also have been selected by the foreground scheduler, if it were in the foreground queue. Worse, putting a subset of equally important requests onto the freeblock queue reduces the options of the

Function Name	Arguments	Description
freeblock_readblocks	*diskaddrs, blksize, callback*	Register freeblock read request(s)
freeblock_writeblocks	*diskaddrs, blksize, buffers, callback*	Register freeblock write request(s)
freeblock_abort	*diskaddrs, blksize*	Abort registered freeblock request(s)
freeblock_promote	*diskaddrs, blksize*	Promote registered freeblock request(s)
**(callback)*	*diskaddr, blksize, buffer*	Call-back to task with desired block

Table 1: **A simple interface to a freeblock subsystem.** *freeblock_readblocks* and *freeblock_writeblocks* register one or more single-block freeblock requests, with an application-defined block size. *freeblock_abort* and *freeblock_promote* are applied to previously-registered requests, to either cancel pending freeblock requests or convert them to foreground requests. When promoted, multiple contiguous freeblock requests can be merged into a single foreground request. **(callback)* is called by the freeblock subsystem to report availability of a single previously-requested block. When the request was a read, *buffer* points to a buffer containing the desired data. The freeblock subsystem reclaims this buffer when **(callback)* returns, meaning that the callee must either process the data immediately or copy it to another location before returning control.

foreground scheduler and may increase the total amount of mechnical positioning overhead.

Large sets of desired blocks. Since freeblock schedulers work with restricted free bandwidth opportunities, their effectiveness tends to increase when they have more options. That is, the larger the set of disk locations that are desired, the higher the probability that a free bandwidth opportunity can be matched to a need. Therefore, tasks that involve larger fractions of the disk's capacity generally utilize larger fractions of the potential free bandwidth.

No particular order of access. Ordering requirements restrict the set of requests that can be considered by the scheduler at any point in time. Since the effectiveness of freeblock scheduling is directly related to the number of outstanding requests, workloads with little or no ordering requirements tend to utilize more of the potential free bandwidth.

Small working memory footprints. Significant need to buffer multiple blocks before processing them causes memory limitations to create artificial ordering requirements. Workloads that can immediately process and discard data from freeblock requests tend to be able to request more of their needed data at once.

To clarify the types of tasks that fit the freeblock model, Table 1 presents a sample interface for a freeblock subsystem, ignoring component and protection boundary issues. This interface is meant to be illustrative only; a comprehensive API would need to address memory allocation, protection, and other issues.

This sample freeblock API has four important characteristics. First, no call into the

freeblock subsystem waits for a disk access. Instead, calls to register requests return immediately, and subsequent callbacks report request completions. This allows applications to register large sets of freeblock requests. Second, block sizes are provided with each freeblock request, allowing applications to ensure that useful units are provided to them. Third, read requests do not specify memory locations for read data. Completion callbacks provide pointers to buffers owned by the freeblock subsystem and indicate which requested data blocks are in them. This allows tasks to register many more freeblock reads than their memory resources would otherwise allow, giving greater flexibility to the freeblock subsystem. For example, the data mining example in Section 6 starts by registering freeblock reads for all blocks on the disk. Fourth, freeblock requests can be aborted or promoted to foreground requests at any time. The former allows tasks to register for more data than are absolutely required (e.g., a search that only needs one match). The latter allows tasks to increase the priority of freeblock requests that may soon impact foreground task performance (e.g., a space compression task that has not made sufficient progress).

2.2 Applications

Freeblock scheduling is a new tool, and we expect that system designers will find many unanticipated uses for it. This section describes some of the applications we see for its use.

Scanning applications. In many systems, there are a variety of support tasks that scan large portions of disk contents. Such activities are of direct benefit to users, although they may not be the highest priority of the system. Examples of such tasks include report generation, virus detection, tamper detection [27], and back-up. Section 6 explores data mining of an active transaction processing system as a concrete example of such use of free bandwidth.

These disk-scanning application tasks are ideal candidates for free bandwidth utilization. Appropriately structured, they can exhibit all four of the desirable characteristics discussed above. For example, report generation tasks (and data mining in general) often consist of collecting statistics about large sets of small, independent records. These tasks may be of lower priority than foreground transactions, access a large set of blocks, involve no ordering requirements, and process records immediately. Similarly, virus detectors examine large sets

of files for known patterns. The files can be examined in any order, though internal statistics for partially-checked files may have significant memory requirements when pieces of files are read in no particular order. Backup applications can be based on physical format, allowing flexible block ordering with appropriate indices, though single-file restoration is often less efficient [23, 11]. Least flexible of these examples would be tamper detection that compares current versions of data to "safe" versions. While the comparisons can be performed in any order, both versions of a particular datum must be available in memory to complete a comparison. Memory limitations are unlikely to allow arbitrary flexibility in free bandwidth utilization.

Internal storage optimization. Another promising use for free bandwidth is internal storage system optimization. Many techniques have been developed over the years for reorganizing stored data to improve performance of future accesses. Examples include placing related data contiguously for sequential disk access [31, 46], placing hot data near the center of the disk [45, 40, 3], and replicating data on disk to provide quicker-to-access options for subsequent reads [34]. Other examples include index reorganization [22, 17] and compression of cold data [8]. Section 5 uses segment cleaning in log-structured file systems as a concrete example of such use of free bandwidth.

While the activities of internal storage optimization exhibit the first two qualities listed in section 2.1, they can pose some ordering and memory restrictions on media accesses. For example, reorganization generally requires clearing (i.e., reading or moving) destination regions before different data can be written there. Also, after opportunistically reading data for reorganization, the task must write this data to their new locations. Eventually, progress will be limited by the rate at which these writes can be completed, since available memory resources for buffering such data are finite.

Prefetching and Prewriting. Another use of free bandwidth is for anticipatory disk activities such as prefetching and prewriting. Prefetching is well-understood to offer significant performance enhancements [36, 6, 19, 30]. Free bandwidth prefetching should increase performance further by avoiding interference with foreground requests and by minimizing the opportunity cost of aggressive predictions. Still, the amount of prefetched data is necessarily limited by the amount of memory available for caching, restricting the number of freeblock

requests that can be issued.

Prewriting is the same concept in reverse. That is, prewriting is early writing out of dirty blocks with the assumption that they will not be overwritten or deleted before write-back is actually necessary. As with prefetching, the value of prewriting and its relationship with non-volatile memory are well-known [4, 7, 5, 17]. Free bandwidth prewriting has the same basic benefits and limitations as free prefetching.

3 Availability of Free Bandwidth

This section quantifies the availability of potential free bandwidth, which is equal to a disk's total potential bandwidth multiplied by the fraction of time it spends on rotational latency delays. The amount of rotational latency delay depends on a number of disk, workload, and scheduling algorithm features.

The experimental data in this section were generated with the DiskSim [16] simulator, which has been shown to accurately model several modern disk drives [13], including those explored here. By default, the experiments use a Quantum Atlas 10K disk drive and a synthetic workload referred to as *random*. This random workload consists of 10000 foreground requests issued one at a time with no idle time between requests (closed system arrival model with no think time). Other default parameters for the random workload are request size of 4KB, uniform distribution of starting locations across the disk capacity, and 2:1 ratio of reads to writes.

Most of the bar graphs presented in this section have a common structure. Each bar breaks down disk head usage into several regions that add up to 100%, with each region representing the percentage of the total attributed to the corresponding activity. All such bars include regions for foreground seek times, rotational latencies, and media transfers. The rotational latency region indicates the potential free bandwidth (as a percentage of the disk's total bandwidth) available for the disk–workload combination.

	Quantum Atlas 10K	Seagate Cheetah 4LP	Seagate Cheetah 9LP	Seagate Cheetah 18LP	IBM Ultrastar 18ES
Year	1999	1996	1997	1998	1998
Capacity	9 GB	4.5 GB	9 GB	9 GB	9 GB
Cylinders	10042	6581	6962	9772	11474
Sectors per track	229–334	131–195	167–254	252–360	247–390
Spindle speed (RPM)	10025	10033	10025	10025	7200
Average seek	5.0 ms	7.7 ms	5.4 ms	5.2 ms	7.0 ms

Table 2: **Basic characteristics of several modern disk drives.**

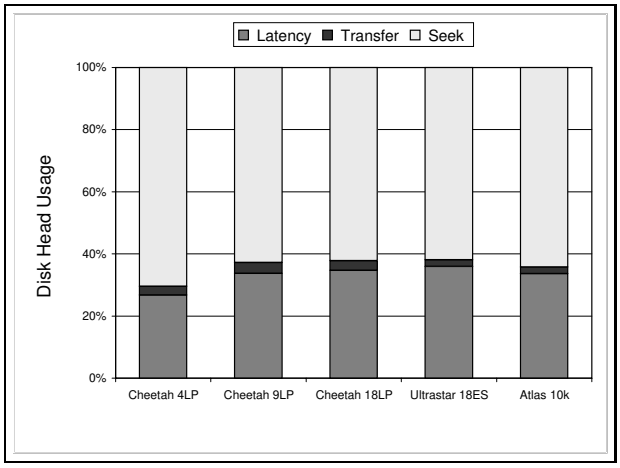


Figure 2: **Disk head usage for several modern disks.**

3.1 Impact of disk characteristics

Figure 2 shows breakdowns of disk head usage for five modern disk drives whose basic characteristics are given in Table 2. Overall, for the random workload, about one third (27–36%) of each disk's head usage can be attributed to rotational latency. Thus, about one third of the media bandwidth is available for freeblock scheduling, even with no inter-request locality.

At a more detailed level, the effect of key disk characteristics can be seen in the breakdowns. For example, the faster seeks of the Cheetah 9LP, relative to the Cheetah 4LP, can be seen in the lower seek component. Also, the slightly lower ratio of average seek time to rotation speed of the IBM 18ES, relative to the Atlas 10K, can be seen in the slightly smaller seek component and slightly larger rotational latency component.

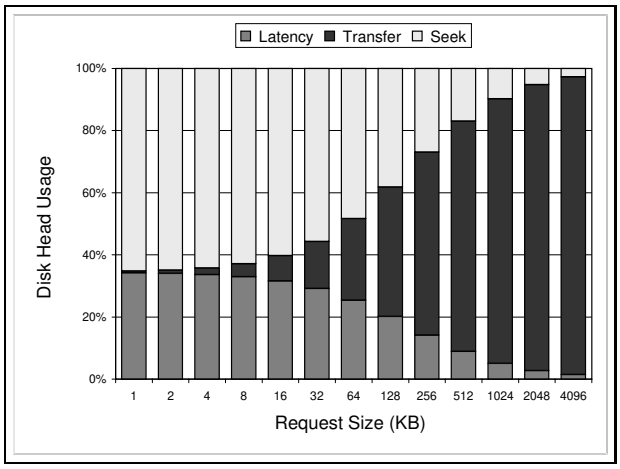


Figure 3: **Disk head usage as a function of request size.**

3.2 Impact of Workload Characteristics

Figure 3 shows how the breakdown of disk head usage changes as the request size of the random workload increases. As expected, larger request sizes yield larger media transfer components, reducing the seek and latency components by amortizing larger transfers over each positioning step. Still, even for large random requests (e.g., 256KB), disk head utilization is less than 55% and potential free bandwidth is 15%.

Figure 4 shows how the breakdown of disk head usage changes as the degree of request locality increases. Because access locality tends to reduce seek distances without directly affecting the other components, this graph shows that both the transfer and latency components increase. For example, when 70% of the requests are within the same "cylinder group" [32] as the last request, almost 60% of the disk head's time is spent in rotational latency and is thus available for freeblock scheduling. Figure 4 does not show the downside (for freeblock scheduling) of high degrees of locality — starvation of distant freeblock requests. That is, if foreground requests keep the disk head in one part of the disk, it becomes difficult for a freeblock scheduler to successfully make progress on freeblock requests in distant parts of the disk.

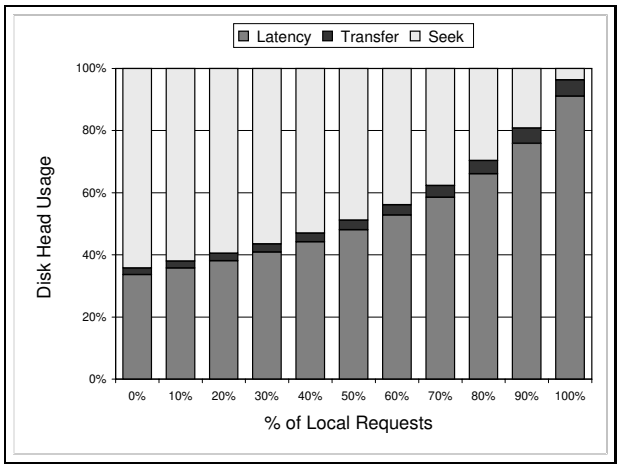


Figure 4: **Disk head usage as a function of request locality.** The default workload was modified such that a percentage of request starting locations are "local" (taken from a normal distribution centered on last requested location, with a standard deviation of 4MB). The remaining requests are uniformly distributed across the disk's capacity. This locality model crudely approximates the effect of "cylinder group" layouts [32] on file system workloads.

3.3 Impact of Scheduling Algorithm

Figure 5 shows how the breakdown of disk head usage changes for different scheduling algorithms applied to foreground requests. Specifically, four scheduling algorithms are shown: First-Come-First-Served (FCFS), Circular-LOOK (C-LOOK), Shortest-Seek-Time-First (SSTF), and Shortest-Positioning-Time-First (SPTF). FCFS serves requests in arrival order. C-LOOK selects the next request in ascending starting address order; if none exists, it selects the request with the lowest starting address. SSTF selects the request that will incur the shortest seek. SPTF selects the request that will incur the smallest overall positioning delay (seek time plus rotational latency).

On average, C-LOOK and SSTF reduce seek times without affecting transfer times and rotational latencies. Therefore, we expect (and observe) the seek component to decrease and the other two to increase. In fact, for this workload, the rotational latency component increases to 50% of the disk head usage. On the other hand, SPTF tends to decrease both overhead components, and Figure 5 shows that the rotational latency component decreases significantly (to 22%) relative to the other scheduling algorithms.

SPTF requires the same basic time predictions as freeblock scheduling. Thus, its supe-

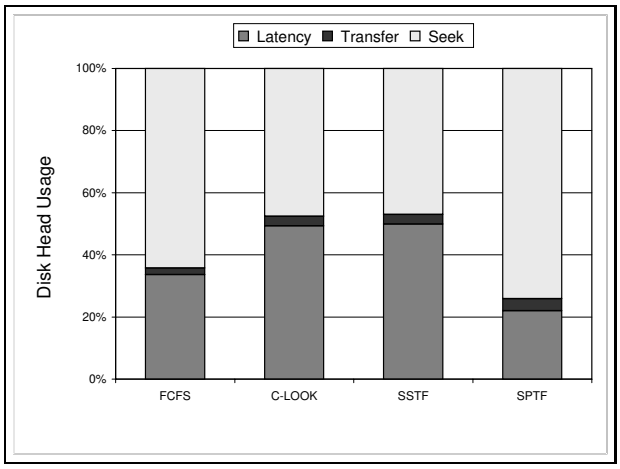
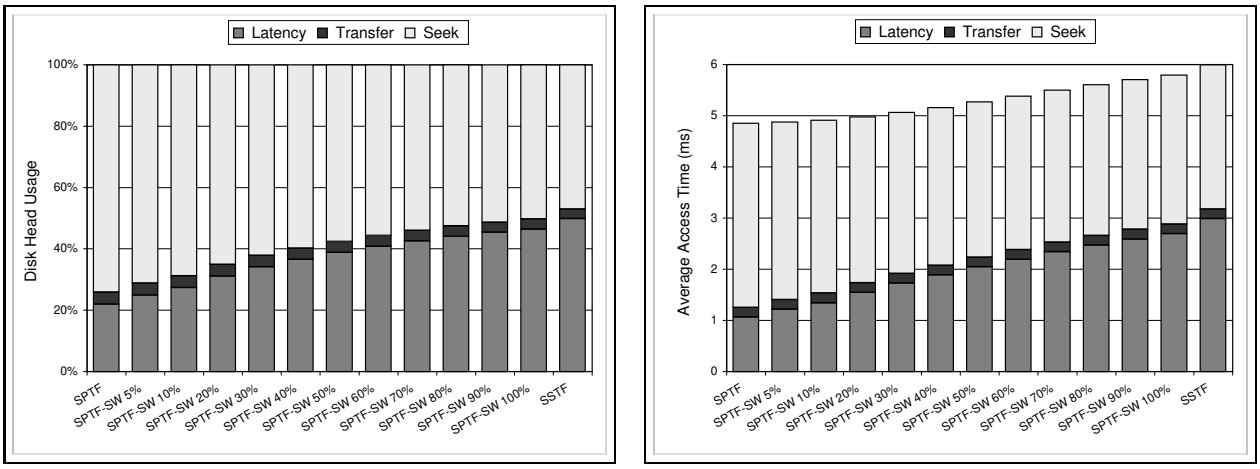


Figure 5: **Disk head usage for several foreground scheduling algorithms.** The default workload was modified to always have 20 requests outstanding. Lowering the number of outstanding requests reduces the differences between the scheduling algorithms.

rior performance will make it a common foreground scheduling algorithm in systems with freeblock scheduling. Unfortunately it's effect on potential free bandwidth is distressing. To counter this effect, we propose a modified SPTF algorithm that is weighted to select requests with both small total positioning delays and large rotational latency components The algorithm, here referred to as SPTF-SWn%, selects the request with the smallest seek time component among the pending requests whose positioning times are within n% of the shortest positioning time. So, logically, this algorithm first uses the standard SPTF algorithm to identify the next most efficient request, denoted A, to be scheduled. Then, it makes a second pass to find the pending request, denoted B, that has the smallest seek time while still having a total positioning time within n% of A's. Request B is then selected and scheduled. This algorithm creates a continuum between SPTF (when $n = 0$) and SSTF (when $n = \infty$), and we expect the disk head usage breakdown to reflect this.

Figure 6 shows the breakdown of disk head usage and the average foreground request access time when SPTF-SWn% is used for foreground request scheduling. As expected, different values of n result in a range of options between SPTF and SSTF. As n increases, seek reduction becomes a priority and the rotational latency component of disk head usage increases. At the same time, average access times increase as total positioning time plays a less dominant role in the decision process. Fortunately, the benefits increase rapidly before



(a) Disk head usage

(b) Average access time

Figure 6: **Disk head usage and average access time with SPTF-SWn% for foreground scheduling.** The default workload was modified to always have 20 requests outstanding.

experiencing diminishing returns and the penalties increase slowly before ramping up. So, using SPTF-SW40% as an example, we see that a 6% increase in average access time can provide 66% more free bandwidth potential (i.e., 36% rotational latency for SPTF-SW40% compared to SPTF's 22%). This represents half of the free bandwidth difference between SPTF and SSTF at much less than the 25% foreground access time difference.

4 Freeblock Scheduling Decisions

This section describes and evaluates the computational overhead of the algorithm used in our experiments for freeblock scheduling, which is the process of identifying free bandwidth opportunities and matching them to pending freeblock requests.

Our freeblock scheduler works independently of the foreground scheduler and maintains separate structures. After the foreground scheduler chooses the next request, B, the freeblock scheduler is invoked. It begins by computing the rotational latency that would be incurred in servicing B; this is the free bandwidth opportunity. This computation requires accurate estimates of disk geometry, current head position, seek times, and rotation speed. The freeblock scheduler then searches its list of pending freeblock requests for the most complete

use of this opportunity; that is, our freeblock scheduler greedily schedules freeblock requests within free bandwidth opportunities based on the number of blocks that can be accessed.

The most complete use of a free bandwidth opportunity can be computed by selecting the maximal answer to the question, "for each track on the disk, how many desired blocks could be accessed in this opportunity?". For each track, t, answering this question requires computing the extra seek time involved with seeking to t and then seeking to B's track, as compared to seeking directly to B's track. Answering this question also requires determining which disk blocks will pass under the head during the remaining rotational latency time and counting how many of them correspond to pending freeblock requests. Note that no extra seek is required for the source track or for B's track.

Obviously, such an exhaustive search can be extremely time consuming. We prune the search space in several ways. First, the freeblock scheduler skips all tracks for which the number of desired blocks is less than the best value found so far. Second, the freeblock scheduler only considers tracks for which the remaining free bandwidth (after extra seek overheads) is greater than the best value found so far. Third, the freeblock scheduler starts by searching the source and destination cylinders (from the previous and current foreground requests), which yield the best choices whenever they are fully populated, and then searching in ascending order of extra seek time. Combined with the first two pruning steps, this ordered search frequently terminates quickly.

The algorithm described above performs well when there is a large number of pending freeblock requests. For example, when 20–100% of the disk is desired, freeblock scheduling decisions are made in 0-2.5ms on a 550MHz Pentium III, which is much less than average disk access times. For such cases, it should be possible to schedule the next freeblock request in real-time before the current foreground request completes, even with a less-powerful CPU. With greater fragmentation of freeblock requests, the time required for the freeblock scheduler to make a decision rises significantly. The worst-case computation time of this algorithm occurs when there are large numbers of small requests evenly distributed across all cylinders. In this case, the algorithm searches a large percentage of the available disk space in the hopes of finding a larger section of blocks than it has already found. Fortunately, search space pruning again provides a solution; instead of an exhaustive search, one can halt

searches after some amount of time (e.g., the time available before the previous foreground request completes). In most cases, this has a negligible effect on the achieved bandwidth. For all experiments in this paper, the freeblock scheduling algorithm was only allowed to search for the next freeblock request in the time that the current foreground request is being serviced. Development of more efficient freeblock scheduling algorithms is an important area for further work.

5 Free cleaning of LFS segments

The log-structured file system [39] (LFS) was designed to reduce the cost of disk writes. Towards this end, it remaps all new versions of data into large, contiguous regions called segments. Each segment is written to disk with a single I/O operation, amortizing the cost of a single seek and rotational delay over a write of large number of blocks. A significant challenge for LFS is ensuring that empty segments are always available for new data. LFS answers this challenge with an internal defragmentation operation called cleaning. Ideally, all necessary cleaning would be completed during idle time, but this is not always possible in a busy system. The potential and actual penalties associated with cleaning have been the subject of heated debate and several research efforts [41]. With freeblock cleaning, the cost can be zero for many workloads.

5.1 Design

Cleaning of a previously written segment involves identifying the subset of live blocks, reading them into memory, and writing them into the next segment. Live blocks are those that have not been overwritten or deleted by later operations; they can be identified by examining the on-disk segment summary structure to determine the original identity of each block (e.g., block 4 of file 3) and then examining the auxiliary structure for the block's original owner (e.g., file 3's i-node). Segment summaries, auxiliary structures, and live blocks can be read via freeblock requests. There are ordering requirements among these, but live blocks can be read in any order and moved into their new locations immediately.

Like other background LFS cleaners, our freeblock segment cleaner is invoked when the

number of empty segments drops below a certain threshold. When invoked, the freeblock cleaner selects several non-empty segments and uses freeblock requests to clean them in parallel with other foreground requests. Cleaning several segments in parallel provides more requests and greater flexibility to the freeblock scheduler. If the freeblock cleaner is not effective enough,the foreground cleaner will be activated when the minimum threshold of free segments is reached.

As live blocks in targeted segments are fetched, they are copied into the in-memory segment that is currently being constructed by LFS writes. Because the live blocks are written into the same segment as data of foreground LFS requests, this method of cleaning is not entirely for free. The auxiliary data structure (e.g., i–node) that marks the location of the block is updated to point to the block's new location in the new segment. When all live blocks are cleaned from a segment on the disk, that segment becomes available for subsequent use.

5.2 Experimental Setup

To experiment with freeblock cleaning, we have modified a log-structured logical disk, called LLD [12]. LLD uses segments consisting of 128 4KB blocks, of which 127 blocks are used for data and one block is used for segment summary. The default implementation of LLD invokes its cleaner only when the number of free segments drops below a threshold (set to two segments). It does not implement background cleaning. Thus, all segment cleaning activity interferes with the foreground disk I/O. We replaced LLD's default segment selection algorithm for cleaning with LFS's cost-benefit algorithm[39], yielding better performance for all of the cleaners.

Our experiments are run under Linux 2.2.14 with a combination of real processing times and simulated I/O times provided by DiskSim. To accomplish this, we merged LLD with DiskSim, using a raw file for the actual data. Computation times between disk I/Os are measured with `gettimeofday`, which in turn uses the Pentium cycle counter. These times are used to advance simulation time in DiskSim, with request completions reported at the next entry into the application/LLD code.

All experiments are run on a 550 MHz Pentium III machine with 256MB of memory.

DiskSim was configured to model a modified Quantum Atlas 10K disk. Specifically, since the maximal size of an LLD disk is 400MB, we modified the disk specifications of Atlas 10K to have only one data surface resulting in a capacity of 1.5GB. Thus, the LLD "partition" occupies about 1/4 of the disk.

To assess the effectiveness of the freeblock cleaner, we used the Postmark v. 1.11 benchmark, which simulates the small-file activity predominant on busy internet servers [25]. Postmark initially creates a pool of files, it then performs a series of transactions, and finally it deletes all files created during the benchmark run. A single transaction is one access to an existing file (i.e., read or append) and one file manipulation (i.e., file creation or deletion). We used the following parameter values: 5–10KB file size (default Postmark value), 25000 transactions, and 100 subdirectories. The number of files in the initial pool was varied to provide a range of file system capacity utilizations. The ratios of read-to-write and create-to-delete were kept at their default values of 1:1.

To age the file system, we run the transaction phase twice and report measurements for only the second iteration. The rationale for running the set of transactions the first time is to spread the blocks of the file system among the segments in order to more closely resemble steady-state operation. Recall that Postmark first creates all files before doing transactions which results in all segments being either completely full or completely empty – a situation very unlikely in normal operation.

5.3 Results

Figure 7 shows Postmark's performance for three different cleaner configurations: ORIGINAL is the default LLD cleaner with the LFS segment selection algorithm. FREEBLOCK is the freeblock cleaner where cleaning reads are freeblock requests and cleaning writes are foreground requests. IDEAL subtracts all cleaning costs from ORIGINAL and computes the corresponding throughput. IDEAL is unrealistic because infinitely fast foreground cleaning is not possible.

Figure 7 shows the transactions per second for different FS space utilizations, corresponding to different numbers of files initially created by Postmark. The high throughput for low utilizations (less than 8% of capacity) is due to the LLD buffer cache, which absorbs

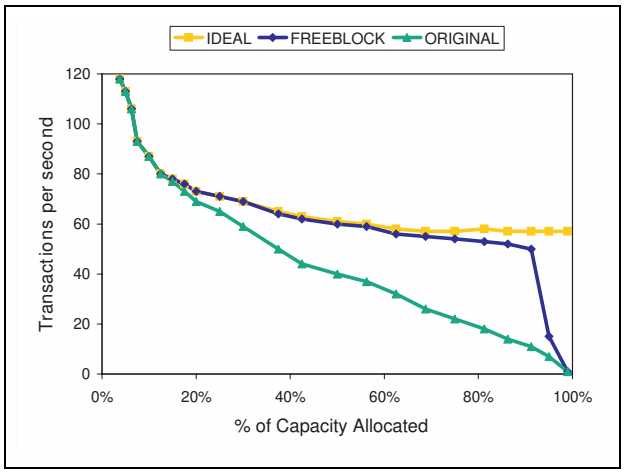


Figure 7: **LLD performance for three cleaning strategies.** Even with a heavy foreground workload(Postmark), segment cleaning can be completed with just freeblock requests until the FS is 93% full.

all of the disk activity. IDEAL's performance decreases as utilization increases, because the larger set of files results in fewer cache hits for Postmark's random file accesses. As disk utilization increases, ORIGINAL's throughput decreases consistently due to cleaning overheads, halving performance at 60% capacity and quartering it at 85%. FREEBLOCK maintains performance close to IDEAL (up to 93% utilization). After 93%, there is insufficient time for freeblock cleaning to keep up with the heavy foreground workload, and the performance of FREEBLOCK degrades as the foreground cleaner increasingly dominates performance. FREEBLOCK's slow divergence from IDEAL occurs between 40% and 93%, because FREEBLOCK is being charged for the write cost of cleaned segments while IDEAL is not.

6 Free data mining on OLTP systems

The use of data mining to elicit patterns from large databases is becoming increasingly popular over a wide range of application domains and datasets [15, 9, 47]. One of the major obstacles to starting a data mining project within an organization is the high initial cost of purchasing the necessary hardware. Specifically, the most common strategy for data mining on a set of transaction data is to purchase a second database system, copy the transaction records from the OLTP system to the second system each evening, and perform mining tasks

only on the second system. This strategy can double the capital and operating expenses. It also requires that a company gamble a sizable up-front investment to test suspicions that there may be interesting "nuggets" to be mined from their OLTP databases.

Data mining can be an excellent application for free bandwidth. Many data mining operations, including nearest neighbor search, association rules [2], ratio and singular value decomposition [28], and clustering [48, 20], eventually translate into a few scans of the entire dataset. Further, these scans parallelize easily, and individual records can be processed immediately and in any order, matching three of the criteria fo effective freeblock functions. In addition, through the use of processing directly on disk drives, smart disk systems [38, 1, 26], can perform many of these algorithms directly at the disk drives, making the media bandwidth at the disks the limiting factor. Riedel, et al., argue that Active Disks and freeblock scheduling make it possible for a significant amount of data mining to be performed on an active OLTP system, without the expense of a second dedicated system for mining tasks [37].

6.1 Design

The Active Disks plus freeblock scheduling approach works well for data mining applications that can be specified abstractly as:

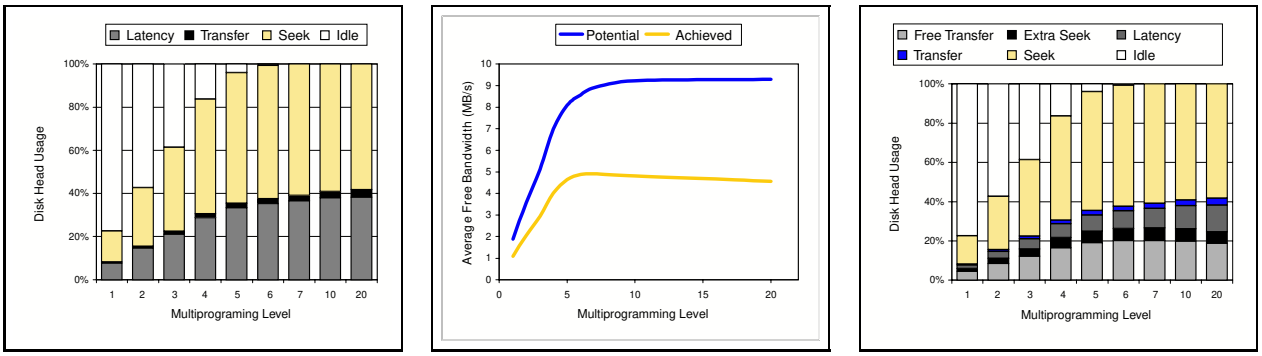
foreach block(B) *in* relation(X) (1)
  filter(B) $\rightarrow B'$ (2)
  combine(B') $\rightarrow$ result(Y) (3)

where steps (1) and (2) can be performed directly at the disk drives in parallel and for any ordering of the blocks, and step (3) combines the results from all the disks at the host after the per-disk scans complete. The freeblock scheduler can ensure that only blocks of a particular application-specific size (e.g., database pages) are provided and that all the blocks requested are read exactly once, but the order of blocks will be determined by the pattern of the foreground OLTP requests. When step (2) is operating directly at Active disk drives, the blocks can be immediately processed, without ever having to be transferred to the host.

Applications that fit this model — low computation cost for the filter function and high selectivity (large data reduction) from B to B' — will be limited by the raw bandwidth available from the disk media. In a dedicated mining system, this bandwidth would be the full sequential bandwidth of the individual disks. However, even in a system running a heavy transaction processing workload, freeblock scheduling can provide a significant fraction of the available media bandwidth.

6.2 Experimental Setup

The experiments in Section 6.3 were conducted using the DiskSim simulator configured to model the Quantum Atlas 10K and a synthetic foreground workload based on approximations of observed OLTP workload characteristics. The synthetic workload models a closed system with per-task disk requests separated by think times of 30 milliseconds. We vary the multiprogramming level (MPL), or number of tasks, of the OLTP workload to illustrate increasing foreground load on the system. For example, a multiprogramming level of 10 means that there are ten requests active in the system at any given point, either queued at one of the disks or waiting in think time. The OLTP requests are uniformly-distributed across the disk's capacity with a read to write ratio of 2:1 and a request size that is a multiple of 4 kilobytes chosen from an exponential distribution with a mean of 8 kilobytes. Validation experiments (in [37]) show that this workload is sufficiently similar to disk traces of Microsoft's SQL server running TPC-C for the overall freeblock-related insights to apply to more realistic OLTP environments. All simulations run for the time required for the background data mining workload to complete ten full disk scans, and the results presented are averages across these 10 scans. The background data mining workload uses free bandwidth to make full scans of the disk's contents in 4 KB blocks, completing one scan before starting the next. The experiments ignore record processing overheads, assuming that media scan times dominate.



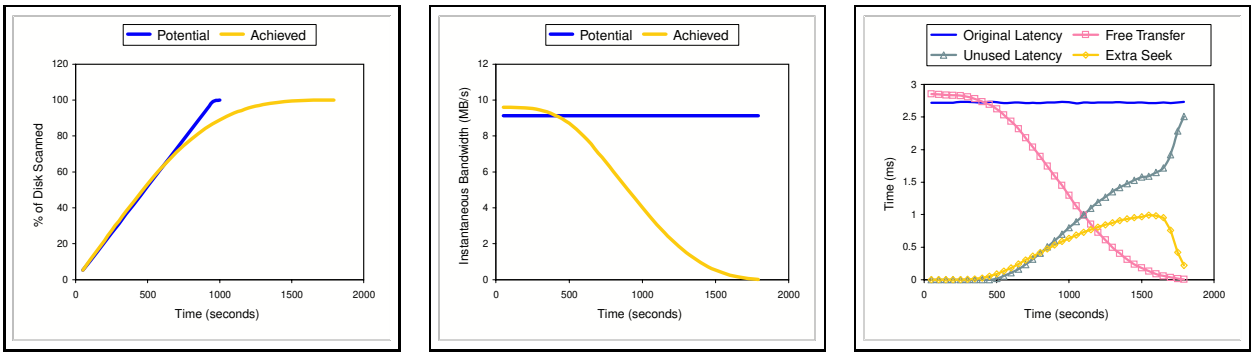
(a) OLTP disk head usage (b) Free mining bandwidth (c) Combined head usage

Figure 8: **Average freeblock-based data mining performance.** (a) shows the disk head usage breakdown for the foreground OLTP workload at various MPLs. (b) shows the overall free bandwidth delivered to the data mining application for the same points. (c) shows the disk head usage breakdown with both the foreground OLTP workload and the background data mining application.

6.3 Results

Figure 8 shows the disk head usage for the foreground OLTP workload at a range of MPLs and the free bandwidth achieved by the data mining task. Low OLTP loads result in low data mining throughput, because little potential free bandwidth exists when there are few foreground requests. Instead, there is a significant amount of idle disk head time that could be used for freeblock requests, albeit not without some effect on foreground response times. Our study here focuses strictly on use of free bandwidth. As the foreground load increases, opportunities to service freeblock requests are more plentiful, increasing data mining throughput to about 4.9 MB/s (about 21% of the Atlas 10K's 23MB/s full potential bandwidth). This represents a 7× increase in useful disk head utilization, from 3% to 24%, and it allows the data mining application to complete over 47 full "scans per day" [18] of this 9GB disk with no effect on foreground OLTP performance.

However, as shown in Figure 8b, freeblock scheduling realizes only half of the potential free bandwidth for this environment. 18% of the remaining potential is lost to extra seek time, which occurs when freeblocks are only available on a third track (other than the previous and current foreground request). The remaining 28% continues to be rotational latency, either as part of freeblock requests or because no freeblock request could be serviced within the available slot.

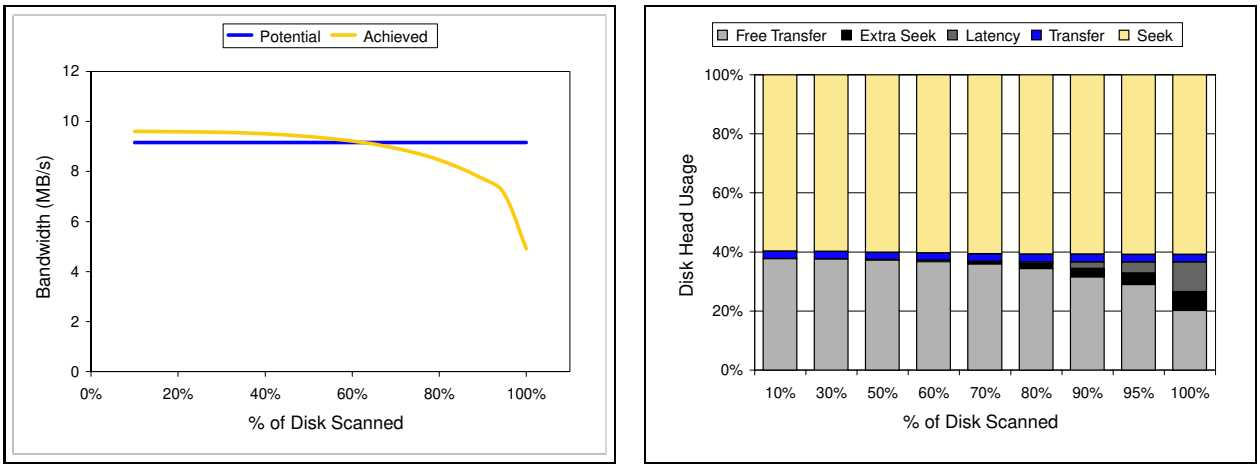


(a) Percent complete (b) Instantaneous free BW (c) Per-requests breakdown

Figure 9: **Freeblock-based data mining progress for MPL 7.** (a) shows the potential and achieved scan progress. (b) shows the corresponding instantaneous free bandwidth curves. (c) shows the usage of potential free bandwidth (i.e., original OLTP rotational latency), partitioning it into free transfer time, extra seek time, and unused latency. As expected, the shape of the free transfer time line matches that of the achieved instantaneous mining bandwidth. Both exceed the potential free bandwidth early in the scan because many foreground transfers can also be used by the freeblock scheduler when most blocks are still needed.

Figure 9 helps to explain why only half of the potential free bandwidth is realized for data mining. Specifically, it shows data mining progress and per-OLTP-request breakdown as functions of the time spent on a given disk scan. The main insight here is that the efficiency of freeblock scheduling (i.e., achieved free bandwidth divided by potential free bandwidth) drops steadily as the set of still-desired background blocks shrinks. As the freeblock scheduler has more difficulty finding conveniently-located freeblock requests, it must look further and further from the previous and current foreground requests. As shown in Figure 9c, this causes extra seek times to increase. Unused rotational latency also increases as freeblock requests begin to incur some latency and as increasing numbers of foreground rotational latencies are found to be too small to allow any pending freeblock request to be serviced. As a result, servicing the last few freeblock requests of a full scan takes a long time; for example, the last 5% of the freeblock requests take 30% of the total time for a scan.

One solution to this problem would be to increase the priority of the last few freeblock requests, with a corresponding impact on foreground requests. The challenge would be to find an appropriate trade-off of impact on the foreground versus improved background performance.



(a) Free mining bandwidth

(b) Disk head usage

Figure 10: **Freeblock-based data mining performance for statistical queries.** Here, it is assumed that any X% of disk's data satisfy the needs of each query scan. Below 60%, achieved free bandwidth exceeds potential free bandwidth, because of the ability to satisfy freeblocks from foreground transfers

An alternate solution would be to take advantage of the nature of many data mining queries, which look for statistical features and correlations within large numbers of records. Statistical sampling has been shown to provide accurate results for many queries and internal database operations after accessing only a (randomly-selected) subset of the total dataset[35, 10]. Figure 10 shows the impact of such statistical data mining as a function of the percentage of the dataset needed. Assuming that freeblock scheduling within the foreground OLTP workload results in sufficiently random data selection or that the sampling algorithm is adaptive to sampling biases[10], sampling can significantly increase freeblock scheduler efficiency. When any 95% of the dataset is sufficient, efficiency is 40% higher than for full disk scans. For 80% of the dataset, efficiency is at 90% and data mining queries can complete over 90 samples of the dataset per day.

7 Related Work

System designers have long struggled with disk performance, developing many approaches to reduce mechanical positioning overheads and to amortize these overheads over large media transfers. When effective, all of these approaches increase disk head utilization for foreground

workloads and thereby reduce the need for and benefits of freeblock scheduling; none have yet eliminated disk performance as a problem. The remainder of this section discusses work specifically related to extraction and use of free bandwidth.

The characteristics of background workloads that can most easily utilize free bandwidth are much like those that can be expressed well with dynamic set [44] and disk-directed I/O [29] interfaces. Specifically, these interfaces were devised to allow application writers to expose order-independent access patterns to storage systems. Application-hinted prefetching interfaces [6, 36] and cache management algorithms [36] share some of these same qualities. Such interfaces may also be appropriate for specifying background activities to freeblock schedulers.

Use of idle time to handle background activities is a long-standing practice in computer systems. A subset of the many examples, together with a taxonomy of idle time detection algorithms, can be found in [17]. Freeblock scheduling complements exploitation of idle time. It also enjoys two superior qualities: (1) ability to make forward progress during busy periods and (2) ability to make progress with **no** impact on foreground disk access times. Starting a disk request during idle time can increase the response time of subsequent foreground requests, by making them wait or by moving the disk head.

In their exploration of write caching policies, Biswas, et al., evaluate a free prewriting mechanism called *piggybacking* [5]. Although piggybacking only considers blocks on the destination track or cylinder, they found that most write-backs could be completed for free across a range of workloads and cache sizes. Relative to their work, our work generalizes both the freeblock scheduling algorithm and the uses for free bandwidth.

Freeblock scheduling relies heavily on the ability to accurately predict mechanical positioning delays (both seek times and rotational latencies). The firmware of most high-end disk drives now support Shortest-Positioning-Time-First (SPTF) scheduling algorithms, which require similar predictions. Based on this fact, we are confident that freeblock scheduling is feasible. However, as is currently true of SPTF scheduling, it may only be possible within disk drive firmware, where complete knowledge of current state and internal algorithms is available. (We are not aware of successful attempts to perform general-purpose SPTF-like scheduling from outside of modern disk drives.)

The Cello disk scheduling framework [43] was designed to allow different classes of disk requests to be merged effectively. Specifically, it was designed for merging non-real-time requests with real-time request streams without causing real-time requests to miss their deadlines. To accomplish this, Cello allows class-specific schedulers to insert requests into a serial class-independent schedule if they pass certain tests (e.g., the newly-inserted request must not cause any already-scheduled request to miss its deadline or exceed its proportion). It is possible that freeblock scheduling could be built into this framework as an extension to the class-independent scheduler.

While freeblock scheduling can provide free media bandwidth, use of such bandwidth also requires some CPU, memory, and bus resources. One approach to addressing these needs is to augment disk drives with extra resources and extend disk firmware with application-specific functionality [1, 26, 38]. Potentially, such resources could turn free bandwidth into free functionality. Such integration is one of the more compelling reasons for the "Active Disk" concept.

Another interesting use of accurate access time predictions and layout information is *eager writing*, or remapping new versions of disk blocks to free locations very near the disk head [21, 14, 33, 46]. We believe that eager writing and freeblock scheduling are strongly complementary concepts. Although eager writing decreases available free bandwidth during writes by eliminating many seek and rotational delays, it does not do so for reads. Further, as with the LFS cleaning example in Section 5, free bandwidth represents an excellent resource for cleaning and reorganization enhancements [46].

8 Conclusions

This paper describes freeblock scheduling, quantifies its potential under various conditions, and demonstrates its value for two specific application environments. By servicing background requests in the context of mechanical positioning for normal foreground requests, 20–50% of a disk's potential bandwidth can be obtained with no impact on the original requests. This paper shows that this free bandwidth can be used to clean LFS segments on busy file servers and to mine data on active transaction processing systems. While addi-

tional experience is needed to refine and realize freeblock scheduling in practice, these results indicate significant promise.

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