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PLACEMENT OF CONTINUOUS MEDIA IN MULTI-ZONE DISKS

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ABSTRACT

For applications with large data sets, e.g., video servers, magnetic disks have established themselves as the mass storage device of choice. A technique to increase the storage capacity of disks is zoning. A side-effect of zoning is that it introduces a disk drive with variable transfer rates. This chapter describes techniques to support a continuous display of constant-bit rate video and audio objects using a multi-zone disk drive. As compared to previous approaches, the proposed techniques harness the average transfer rate of each magnetic disk (instead of its minimum transfer rate). In addition, we describe a configuration planner that logically manipulates the zoning information of a disk drive to support the performance criteria of an application. We present performance numbers from an experimental prototype to demonstrate the feasibility of our approach.

1 INTRODUCTION

A technological trend in the area of magnetic disks is an increase in their storage capacity (a 25% increase a year). Zoning is one approach to accomplish this. A side effect of zoning is that it introduces a disk drive with variable transfer rates: the different regions of a disk drive, termed zones, provide different transfer rates. For example, a Seagate ST31200W disk consists of 23 zones with bandwidths varying from 2.33 to 4.17 megabytes per second (MB/s), see Table 1b. A number of studies have investigated techniques to support a hiccup-free display of continuous media, video and audio, using magnetic disk drives with a single zone [1, 2, 3, 6, 9, 18, 19, 20, 22, 23, 25]. These studies assume a fixed transfer rate for a disk drive. If a system designer elects to use one of

these techniques with multi-zone disks, the system is forced to use the minimum transfer rate of the zones for the entire disk in order to guarantee a continuous display of video objects. We term these studies collectively as minimum transfer rate zone designs, Min-Z-tfr.

This chapter introduces two alternative techniques, VARB and FIXB, that harness the average transfer rate of zones while ensuring a continuous display. When compared with each other and Min-Z-tfr, these techniques impact several system parameters: the percentage of wasted disk space, the number of simultaneous displays (i.e., throughput) supported by the disks, the maximum startup latency incurred by a display, and the amount of memory required by the displays. (Startup latency is defined as the amount of time elapsed from when the request arrives until the onset of its display.) In general, FIXB and VARB increase the throughput of system. For example, assuming the bandwidth required to display an object is 1.5 Mb/s, the proposed techniques enable a Seagate 31200W disk to support 17 simultaneous displays as compared to 12 with Min-Z-tfr, resulting in a 40% improvement in system throughput. However, when restricted to employ the physical zone configuration provided by the vendor, both FIXB and VARB: 1) increase startup latency, 2) waste disk space, and 3) increase the amount of memory required to support 17 simultaneous displays. This chapter describes a configuration planner that consumes the performance requirements of an application, and logically manipulates the zoning information to support the performance criteria of an application with the objective to minimize system cost. The experimental results (see Section 5) indicate that the output of the planner almost always provides significant savings as compared to Min-Z-tfr. Min-Z-tfr cannot outperform our planner because it is simulated as one of the possible configurations.

Our target hardware platform consists of a hierarchy of storage devices: memory (DRAM), D magnetic disks, and one or more tertiary storage devices. When compared with each other, the tertiary storage device provides the cheapest storage cost (desirable) while the memory provides the fastest access time (desirable). However, the tertiary storage device is slow (undesirable) while memory is expensive (undesirable). The data resides permanently on the tertiary storage device. The working set of an application is rendered disk resident to minimize the number of references to the tertiary storage devices. The working set [8] of an application consists of those objects that are referenced repeatedly during a fixed interval of time. For example, in existing video stores, a few titles are expected to be accessed frequently and a store maintains several (sometimes many) copies of these titles to satisfy the expected demand. These titles constitute the working set of a video-on-demand server. When a display references an object, memory is used to stage a portion of the object for imme-

diate display. The speed of memory can hide the latency of other two storage devices to provide for a display that is free of disruptions and delays [10, 15].

Consider the tradeoffs associated with FIXB, VARB, and Min-Z-tfr in this architecture. First, trading system latency for a higher throughput is dependent on the requirements of the target application. For example, with a video-on-demand system that provides service to a city, it is reasonable to expect the clients to tolerate a latency in the order of minutes (previewing commercials) in order to support a higher number of simultaneous displays (throughput). However, with a news-on-demand service where a typical news clip lasts approximately a few minutes, expecting the clients to tolerate a latency in the order of minutes may not be reasonable. In this environment, it might be more appropriate to reduce the throughput in favor of a lower latency time. Second, the significance of wasted disk space is dependent on: (1) the size of an application's working set, and (2) the remaining disk space. If the remaining disk space can materialize the working set of an application then the impact of the wasted space is marginal. Otherwise, the amount of wasted space might reduce system performance due to frequent references to the tertiary storage device. (A tertiary storage device has a higher latency than a magnetic disk drive.) In this chapter, we develop a methodology to quantify the impact of wasted disk space. This methodology is employed to compare the alternative techniques with one another.

The rest of this chapter is organized as follows. After a brief introduction to magnetic disk drives, we describe FIXB and VARB using a single disk drive. Subsequently, Section 6 extends our techniques to a multi-disk hardware platform. Our conclusion and future research directions are contained in Section 7.

2 OVERVIEW OF A MAGNETIC DISK DRIVE

A magnetic disk drive is a mechanical device, operated by its controlling electronics. The mechanical parts of the device consist of a stack of platters that rotate in unison on a central spindle (see [21] for details). Presently, a single disk contains one, two, or as many as sixteen platters. Each platter surface has an associated disk head responsible for reading and writing data. Each platter stores data in a series of tracks. A single stack of tracks at a common distance from the spindle is termed a cylinder. To access the data stored in a track, the disk head must be positioned over it. The operation to reposition the

Zone #	Size (MB)	Transfer Rate (MB/s)
0	324.0	3.40
1	112.0	3.17
2	76.0	3.04
3	77.0	2.92
4	71.0	2.78
5	145.0	2.54
6	109.0	2.27
7	89.0	2.02

(a) Hewlett-Packard C2247 disk

Zone #	Size (MB)	Transfer Rate (MB/s)
0	140.0	4.17
1	67.0	4.08
2	45.0	4.02
3	46.0	3.97
4	44.0	3.88
5	42.0	3.83
6	41.0	3.74
7	56.0	3.60
8	39.0	3.60
9	37.0	3.50
10	52.0	3.36
11	35.0	3.31
12	34.0	3.22
13	46.0	3.13
14	32.0	3.07
15	31.0	2.99
16	42.0	2.85
17	28.0	2.76
18	27.0	2.76
19	37.0	2.62
20	25.0	2.53
21	34.0	2.43
22	20.0	2.33

(b) Seagate ST31200W disk

Table 1 Two commercial disks and their zoning information

head from the current track to the desired track is termed *seek*. Next, the disk must wait for the desired data to rotate under the head. This time is termed *rotational latency*.

To meet the demands for a higher storage capacity, disk drive manufacturers have introduced disks with *zones*. A zone is a contiguous collection of disk

cylinders whose tracks have the same storage capacity. Tracks are longer towards the outer portions of a disk platter as compared to the inner portions, hence, more data may be recorded in the outer tracks. While zoning increases the storage capacity of the disk, it produces a disk that does not have a single transfer rate. The multiple transfer rates are due to (1) the variable storage capacity of the tracks and (2) a fixed number of revolutions per second for the platters. Table 1 presents the zone characteristics of two commercial disk drives. Both are SCSI-2 fast and wide disks with a 1 gigabyte storage capacity.

A disk performs useful work when transfering data and wasteful work when performing seek operation. The seek time is a function of the distance traveled by the disk arm [4, 17, 21, 24]. Several studies have introduced analytical models to estimate seek time as a function of this distance. Other studies have investigated techniques to minimize the seek time [5, 7, 12, 25]. One approach is based on *Constrained* allocation. It controls the placement of blocks of different objects on the disk surface to minimize the distance traveled by the disk arm. Our proposed techniques employ this approach to localize block references to a single zone. Hence, when multiplexing the disk bandwidth among retrieval of $\mathcal{N}$ blocks, the incurred seek time is bounded by the maximum seek time within a zone. Let $Seek(k)$ denote the time required for the disk arm to travel k cylinders to reposition itself from cylinder i to cylinder $i+k$ (or $i-k$). Hence, assuming a disk with $\#cyl$ cylinders, $Seek(1)$ and $Seek(\#cyl)$ denote the time required to reposition the disk arm between two adjacent cylinders, and the first and the last cylinder of the disk, respectively. Consequently, the average time required to seek among the cylinders of a zone i with $\#zcyl_i$ cylinders is is $Seek(\#zcyl_i)$. In Section 4, this model becomes more complex because our planner logically combines two physically adjacent zones and treats them as a single zone. The worst seek time of this zone is now higher because its total number of cylinders increases. We eliminate this factor from discussion by using a constant worst seek time for each zone. We made this simplifying assumption in order to focus on variable transfer rate of a magnetic disk drive (instead of seek time that has been investigated by several other studies [5, 7, 12, 22, 25]). The extensions of this study to incorporate the variable worst seek time for the reads localized to a zone is straightforward.

3 SINGLE DISK PLATFORM

This section presents two alternative designs to support a continuous display of video objects using a single disk. We assume the following:

1. a disk with m zones: Z_0, Z_1, ..., Z_{m-1}. The transfer rate of zone i is denoted as $\mathcal{R}(Z_i)$. Z_0 denotes the outermost zone with the highest transfer rate: $\mathcal{R}(Z_0) \geq \mathcal{R}(Z_1) \geq ... \geq \mathcal{R}(Z_{m-1})$.
2. a single media type with a fixed display bandwidth, $\mathcal{R}_C$.
3. the display bandwidth is less than or equal to the average transfer rate of the disk, $\mathcal{R}_C \leq \frac{\sum_{i=0}^{m-1} \mathcal{R}(Z_i)}{m}$. This assumption is relaxed in Section 6.

The two proposed techniques partition each object X into f blocks: X_0, X_1, X_2, ..., X_{f-1}. The first, termed FIXB, renders the blocks equi-sized. With the second technique, termed VARB, the size of a block depends on the transfer rate of its assigned zone. The advantage of FIXB is its ease of implementation. There are two reasons for this claim. First, a fixed block size simplifies the implementation of a file system that serves as the interface between memory and magnetic disk drive. Second, the design and implementation of a memory manager with fixed frames (the size of a frame corresponds to the size of a block) is simpler than one with variable sized frames. This is particularly true in the presence of multiple displays that result in race conditions when competing for the available memory[1]. While VARB might be more complicated to implement, it requires a lower amount of memory and incurs a lower latency as compared to FIXB when the bandwidth of the disk drive is a scarce resource. FIXB and VARB share many common characteristics. In Section 3.1, we describe FIXB. Subsequently, Section 3.2 describes VARB and its differences as compared to FIXB. Section 3.3 quantifies the tradeoffs associated with these two techniques. The performance numbers from an implementation of FIXB are reported in Section 3.4. These results validate the analytical models.

3.1 Fixed Block Size, FIXB

With this technique, the blocks of an object X are rendered equi-sized. Let $\mathcal{B}$ denote the size of a block. The system assigns the blocks of X to the zones in a round-robin manner starting with an arbitrary zone. FIXB configures the system to support a fixed number of simultaneous displays, $\mathcal{N}$. This is achieved by requiring the system to scan the disk in one direction, say starting with the outermost zone moving inward, visiting one zone at a time and multiplexing

[1] We have participated in the design, coding, and debugging of a multi-user buffer pool manager with a fixed block size for a relational storage manager. We explored the possibility of extending this buffer pool manager to support variable block size, and concluded that it required significant modifications.

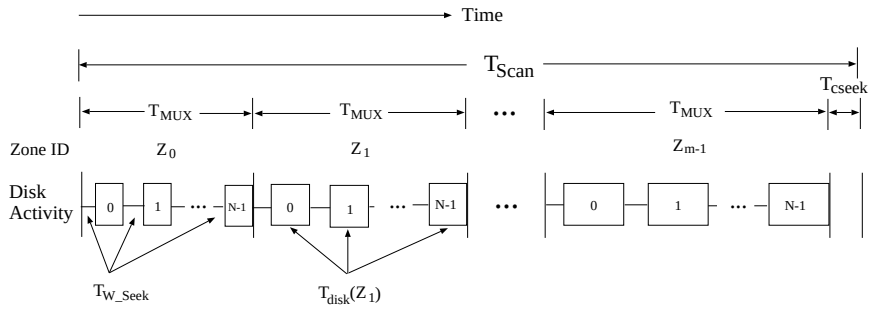


Figure 1 T_{Scan} and its relationship to T_{MUX}

the bandwidth of that zone among $\mathcal{N}$ block reads. Once the disk arm reads $\mathcal{N}$ blocks from the innermost zone, it is repositioned to the outermost zone to start another sweep of the zones. The time to perform one such a sweep is denoted as T_{Scan}. The system is configured to produce and display an identical amount of data per T_{Scan} period. The time required to read $\mathcal{N}$ blocks from zone i, denoted $T_{MUX}(Z_i)$, is dependent on the transfer rate of zone i. This is because the time to read a block ($T_{disk}(Z_i)$) during one $T_{MUX}(Z_i)$ is a function of the transfer rate of a zone.

Figure 1 shows T_{Scan} and its relationship with $T_{MUX}(Z_i)$ for m zones. During each T_{MUX} period, $\mathcal{N}$ active displays might reference different objects. This would force the disk to incur a seek when switching from the reading of one block to another, termed T_{W_Seek}. T_{W_Seek} also includes the maximum rotational latency time. At the end of a T_{Scan} period, the system observes a long seek time (T_{cseek}) attributed to the disk repositioning its arm to the outermost zone. The disk produces m blocks of X during one T_{Scan} period ($m \times \mathcal{B}$ bytes). The number of bytes required to guarantee a hiccup-free display of X during T_{Scan} should either be lower than or equal to the number of bytes produced by the disk. This constraint is formally stated as:

$$\mathcal{R}_C \times (T_{cseek} + \sum_{i=0}^{m-1} T_{MUX}(Z_i)) \leq m \times \mathcal{B} \tag{1.1}$$

The amount of memory required to support a display is minimized when the left hand side of Equation 1.1 equals its right hand side.

During a T_{MUX}, $\mathcal{N}$ blocks are retrieved from a single zone, Z_{Active}. In the next T_{MUX} period, the system references the next zone $Z_{(Active+1) \bmod m}$. When a display references object X, the system computes the zone containing X_0,

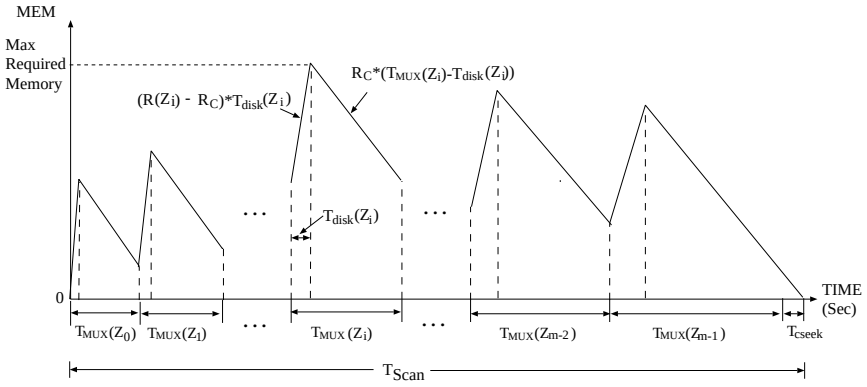


Figure 2 Memory required on behalf of a display

Term	Definition
T_{W_Seek}	Worst seek time of a zone (including the maximum rotational latency time)
T_{cseek}	Seek time required to make a complete span
cap	Total capacity of a disk drive
m	Number of zones in a disk drive
Z_i	Zone i of a disk drive, where $0 \leq i < m$
$\mathcal{R}(Z_i)$	Transfer rate of Z_i, in MB/s
$size(Z_i)$	Capacity of Z_i
$\mathcal{B}(Z_i)$	Block size of Z_i with VARB
$\mathcal{B}$	Fixed block size with FIXB
$\mathcal{G}_i$	Group i, constructed from merging two or more zones
$\mathcal{R}(\mathcal{G}_i)$	Transfer rate of $\mathcal{G}_i$, in MB/s
$size(\mathcal{G}_i)$	Capacity of $\mathcal{G}_i$
T_{scan}	Time to perform one sweep of m zones
$T_{MUX}(Z_i)$	Time to read $\mathcal{N}$ blocks from zone Z_i
$size(WS)$	Size of the application working set
R_C	Display bandwidth requirement (Consumption rate), in MB/s
Mem	Required amount of memory
$\mathcal{N}$	Maximum number of simultaneous displays (throughput)
ℓ	Maximum latency time
$\mathcal{C}$	Total system cost

Table 2 List of terms used repeatedly in this chapter and their respective definitions

say Z_i. The transfer of data on behalf of X does not start until the active zone reaches Z_i. One block of X is transfered into memory per T_{MUX}. Thus, the retrieval of X requires f such periods. (The display of X may exceed $\sum_{j=0}^{f-1} T_{MUX}(Z_{(i+j) \ mod \ m})$ seconds as described below.) The memory requirement for displaying object X varies due to the variable transfer rate. This is best illustrated using an example. Assume that the blocks of X are assigned to the zones starting with the outermost zone, Z_0. If Z_{Active} is Z_0 then this request employs one of the idle $T_{disk}(Z_0)$ slots to read X_0. Moreover, its display can start immediately because the outermost zone has the highest transfer rate. The block size and $\mathcal{N}$ are chosen such that the data accumulates in memory when accessing outermost zones and decreases when reading data from innermost zones on behalf of a display (see Figure 2). In essence, the system uses buffers to compensate for the low transfer rates of innermost zones using the high transfer rates of outermost zones, harnessing the average transfer rate of the disk. Note that the amount of required memory reduces to zero at the end of one T_{scan} in preparation for another sweep of the zones.

The display of an object may not start upon the retrieval of its block from the disk drive. This is because the assignment of the first block of an object may start with an arbitrary zone while the transfer and display of data is synchronized relative to the outermost zone, Z_0. In particular, if the assignment of X_0 starts with a zone other than the outermost zone (say Z_i, $i \neq 0$) then its display might be delayed to avoid hiccups. The duration of this delay depends on: 1) the time elapsed from retrieval of X_0 to the time that block X_{m-i} is retrieved from zone Z_0, termed $T_{accessZ_0}$, and 2) the amount of data retrieved during $T_{accessZ_0}$. If the display time of data corresponding to item 2 ($T_{display(m-i)}$) is lower than $T_{accessZ_0}$, then the display must be delayed by $T_{accessZ_0} - T_{display(m-i)}$. To illustrate, assume that X_0 is assigned to the innermost zone Z_{m-1} (i.e., $i = m-1$) and the display time of each of its block is 4.5 seconds, i.e., $T_{display(1)} = 4.5$ seconds. If 10 seconds elapse from the time X_0 is read until X_1 is read from Z_0 then the display of X must be delayed by 5.5 seconds relative to its retrieval from Z_{m-1}. If its display is initiated upon retrieval, it may suffer from a 5.5 second hiccup. This delay to avoid a hiccup is shorter than the duration of a T_{scan}. Indeed, the maximum latency observed by a request is T_{scan} when the number of active displays is less than[2] $\mathcal{N}$:

$$\ell \ = \ T_{Scan} \ = \ T_{cseek} + \sum_{i=0}^{m-1} T_{MUX}(Z_i) \tag{1.2}$$

[2]When the number of active displays exceeds $\mathcal{N}$ then this discussion must be extended with appropriate queuing models.

This is because at most $\mathcal{N}-1$ displays might be active when a new request arrives referencing object X. In the worst case scenario, these requests might be retrieving data from the zone that contains X_0 (say Z_i) and the new request arrives too late to employ the available idle slot. (Note that the display may not employ the idle slot in the next T_{MUX} because Z_{i+1} is now active and it contains X_1 instead of X_0.) Thus, the display of X must wait one T_{scan} period until Z_i becomes active again.

One can solve for the block size by observing from Figure 1 that $T_{MUX}(Z_i)$ can be defined as:

$$T_{MUX}(Z_i) = \mathcal{N} \times (\frac{\mathcal{B}}{\mathcal{R}(Z_i)} + T_{W\_Seek}) \tag{1.3}$$

Substituting this into Equation 1.1, the block size is defined as:

$$\mathcal{B} = \frac{\mathcal{R}_C \times (T_{cseek} + m \times \mathcal{N} \times T_{W\_Seek})}{m - \mathcal{R}_C \times \sum_{i=0}^{m-1} \frac{\mathcal{N}}{\mathcal{R}(Z_i)}} \tag{1.4}$$

Observe that FIXB wastes disk space when the storage capacity of the zones is different. This is because once the storage capacity of the smallest zone is exhausted then no additional objects can be stored as they would violate a round-robin assignment[3]. Section 3.3 quantifies the percentage of disk space wasted by FIXB for the commercial disks of Table 1.

3.2 Variable Block Size, VARB

VARB is similar to FIXB except that it renders the duration of $T_{MUX}(Z_i)$ identical for all zones. This is achieved by introducing variable block size where the size of a block, $\mathcal{B}(Z_i)$, is a function of the transfer rate of a zone. This causes the transfer time of each block, T_{disk} to be identical for all zones (i.e., $T_{disk}=\frac{\mathcal{B}(Z_i)}{\mathcal{R}(Z_i)}=\frac{\mathcal{B}(Z_j)}{\mathcal{R}(Z_j)}$ for $0 \leq (i,j) < m$). Similar to FIXB, the blocks of an object are assigned to the zones in a round-robin manner and the concept of T_{Scan} is preserved. This means that the blocks of an object X are no longer equi-sized. The size of a block X depends on the zone it is assigned to. However, the change in block size requires a slight modification to the constraint that ensures a continuous display:

$$\mathcal{R}_C \times (T_{cseek} + m \times T_{MUX}) \leq \sum_{i=0}^{m-1} \mathcal{B}(Z_i) \tag{1.5}$$

[3]Unless the number of blocks for an object is less than m. We ignored this case from consideration because video objects are typically very large.

$\mathcal{N}$	*FIXB*	*VARB*		
	Block Size (MBytes)	Minimum Block Size (MBytes)	Maximum Block Size (MBytes)	Average Block Size (MBytes)
1	0.0040	0.0028	0.0050	0.0040
2	0.0083	0.0058	0.0104	0.0082
4	0.0188	0.0132	0.0235	0.0187
8	0.0539	0.0370	0.0663	0.0525
10	0.0863	0.0584	0.1044	0.0828
12	0.1442	0.0949	0.1698	0.1345
13	0.1945	0.1249	0.2236	0.1772
14	0.2773	0.1717	0.3072	0.2434
15	0.4396	0.2540	0.4546	0.3602
16	0.9014	0.4378	0.7835	0.6208
17	12.4333	1.2117	2.1685	1.7183

Table 3 Seagate ST31200W disk

The duration of T_{MUX} is now independent of the transfer rate of a zone and is defined as:

$$T_{MUX} = \mathcal{N} \times (T_{disk} + T_{W\_Seek}) \tag{1.6}$$

Substituting this into Equation 1.5, the size of a block for a zone Z_i is defined as:

$$\mathcal{B}(Z_i) = \mathcal{R}(Z_i) \times \frac{\mathcal{R}_C \times T_{W\_Seek} \times \mathcal{N} \times m + \mathcal{R}_C \times T_{cseek}}{\sum_{i=0}^{m-1} \mathcal{R}(Z_i) - \mathcal{R}_C \times \mathcal{N} \times m} \tag{1.7}$$

Similar to FIXB, VARB employs memory to compensate for the low bandwidth of innermost zones using the high bandwidth of the outermost zones. This is achieved by reading more data from the outermost zones. Moreover, the display of an object X is synchronized relative to the retrieval of its block from the outermost zone and may not start immediately upon retrieval of X_0. VARB wastes disk space when $\frac{size(Z_i)}{\mathcal{R}(Z_i)} \neq \frac{size(Z_j)}{\mathcal{R}(Z_j)}$ for $i \neq j$, and $0 \leq (i, j) < m$. The amount of wasted space depends on the zone that accommodates the fewest blocks. This is because the blocks of an object are assigned to the zones in a round-robin manner and once the capacity of this zone is exhausted the storage capacity of other zones cannot be used by other video objects.

3.3 FIXB vs VARB

$\mathcal{N}$	*FIXB*				*VARB*			
	Mem. (MB)	ℓ (Sec)	% wasted disk space	% Avg wasted band.	Mem. (MB)	ℓ (Sec)	% wasted disk space	% Avg wasted band.
1	0.007	0.44	58.0	94.1	0.011	0.44	40.4	94.3
2	0.023	0.92	58.0	88.2	0.044	0.92	40.4	88.6
4	0.107	2.10	58.0	76.5	0.192	2.08	40.4	77.3
8	0.745	6.03	58.1	53.1	1.059	5.88	40.4	54.6
10	1.642	9.66	58.1	41.4	2.078	9.26	40.5	43.2
12	3.601	16.15	58.2	29.7	4.040	15.06	40.6	31.9
13	5.488	21.77	58.3	23.9	5.759	19.84	40.4	26.2
14	8.780	31.05	58.0	18.0	8.511	27.26	40.6	20.5
15	15.515	49.23	58.4	12.1	13.481	40.34	41.0	14.8
16	35.259	100.9	58.3	6.3	24.766	69.53	41.3	9.2
17	536.12	1392.5	73.8	0.4	72.782	192.4	42.2	3.5

Table 4 Seagate ST31200W disk

While VARB determines the block size as a function of the transfer rate of each individual zone, FIXB determines the block size as a function of the average transfer rate of the zones. In essence, VARB performs local optimization while FIXB performs global optimization. This enables VARB to choose smaller block sizes when compared to FIXB for a fixed number of users. Table 3 presents the required block size as a function of the number of simultaneous displays ($\mathcal{N}$) for a Seagate disk drive[4]. The bandwidth requirement of objects that constitute the database is 1.5 Mb/s ($\mathcal{R}_C$=1.5 Mb/s). The average transfer rate of the disk can support a maximum of 17 simultaneous displays.

A small block size minimizes the duration of T_{Scan} which, in turn, reduces the amount of required memory. This is reflected by the results presented in Table 4. For each of VARB and FIXB, this table presents the required memory, latency[5], percentage of wasted disk space and bandwidth as a function of $\mathcal{N}$. For 17 users, the memory requirement of a system with FIXB is seven times higher than that with VARB. Moreover, the maximum incurred latency is more than 20 minutes with FIXB as compared to 3.25 minutes with VARB.

The percentage of wasted disk space with each of FIXB and VARB is dependent on the physical characteristics of the zones. While VARB wastes a lower percentage of the Seagate disk space, it wastes a higher percentage of the HP disk space (see Table A.2 in Appendix A.1). The average percentage of wasted disk

[4]The numbers for the HP disk drive are contained in Appendix A.1.
[5]Latency is equivalent to the duration of T_{Scan}.

bandwidth is lower with FIXB because it minimizes this value from a global perspective. With VARB, a number of outermost zones waste a higher percentage of their bandwidth in favor of a smaller block size (these zones increase the percentage of wasted disk bandwidth).

3.4 Validation of Analytical Models

To verify the analytical results, we analyzed an implementation of FIXB using MITRA [16]. MITRA is a continuous media server that supports constant-bit rate audio and video objects. It is operational on a cluster of HP 9000/735 workstations (HP/UX 9.05) connected using an ATM switch. A workstation might consist of up to four Seagate disks. This is because the bandwidth of SCSI II bus is exhausted with four disks. The software process structure of MITRA consists of: one scheduler, one disk manager per disk drive, and a player per active display. These components communicate using the UDP protocol. The disk managers perform disk I/O operations while the scheduler implements a file system and the concept of T_{MUX} for retrieving data from each zone. MITRA recognizes each zone as a file system. It can logically treat two physically adjacent zones as a single zone by organizing a single file system across the two zones.

MITRA supports two alternative scheduling paradigms for servicing requests: server-driven and player-driven. With the server-driven paradigm, the scheduler produces data based on the duration of individual T_{MUX} periods. If the retrieval of $\mathcal{N}$ blocks from zone i requires less than $T_{MUX}(Z_i)$ then the server waits for the remaining time before initiating the retrieval of data from zone $i+1$. With the player-driven paradigm, the scheduler starts the retrieval of data from zone $i+1$ as soon as possible. This paradigm assumes that each active player has enough buffers to cache data because it may produce more data for a player when compared with the amount consumed by the player. The maximum amount of memory required from a player is equivalent to the amount of data displayed during one T_{Scan} period (i.e., $T_{Scan} \times \mathcal{R}_{\mathcal{C}}$). This is because the scheduler accepts skip messages from each active player. A player generates a skip message every time the amount of buffered data is equivalent to the maximum available memory. Upon the arrival of this message, the scheduler suspends the retrieval of data on behalf of the player for one T_{Scan} period. The delay must be a multiple of T_{Scan} period due to the constrained placement of data. To illustrate, if the retrieval of data on behalf of a player from zone i is suspended, the required data resides on zone i and this zone becomes active after T_{Scan} time units.

For the purposes of this evaluation, MITRA was configured with a single workstation consisting of a single Seagate ST31200W disk drive. The file system of MITRA recognized each of the twenty-three zones of this disk drive. The database consisted of a collection of CD-quality audio clips. The bandwidth required to play each clip is 1.35 Mb/s. A workload generator issued requests for the different clips. Once the display of an audio clip is done, the workload generator issues a request for another clip (closed model). We used the analytical models of Section 3.1 to compute $\mathcal{B}$ and $T_{MUX}(Z_i)$ for $0 \leq i \leq 22$. A non-linear seek function was used to compute both T_{cseek} and T_{W_Seek} (considering the number of cylinders that the blocks are apart).

If MITRA assumes the minimum transfer rate of the available zones as the transfer rate of the disk, it supports 11 simultaneous streams. By employing FIXB and utilizing the average transfer rate of the zones, the throughput of MITRA using the player-driven paradigm increases to 17 simultaneous streams. Note that since the consumption rate of audio is lower than that of the MPEG-1 video, the analytical models expect MITRA to support 18 simultaneous displays. However, due to the system overheads imposed by the HP/UX operating system, the display of objects suffered from hiccups when MITRA attempts to support 18 simultaneous streams. Consistent with the analytical results, the zone with the minimum storage space (Z_{22}) determined the capacity of the disk drive.

We analyzed the performance of MITRA with the server-driven paradigm. With 17 simultaneous displays, this paradigm suffered from frequent hiccups. The hiccups were attributed to frequent violation of T_{MUX} periods: retrieval of 17 blocks from a zone i exceeded the duration of $T_{MUX}(Z_i)$. Note that the number of times that the retrieval of 17 blocks falls short of $T_{MUX}(Z_i)$ is also frequent allowing the player-driven paradigm to compensate and avoid hiccups. It is interesting to note a player might require 12 megabytes of data (one T_{Scan} period) even though the workload generator issued a new request as soon as an active request completes its display. This is because the retrieval of data on behalf of a newly arriving request starts only when the zone containing its first block (say Z_{X_0}) becomes active. Prior to Z_{X_0} becoming active, MITRA is retrieving at most 16 blocks from each zone. With the player-driven paradigm, MITRA produces more data on behalf of each of these active streams (because the duration of T_{MUX} is shorter than its theoretical value). The minimum and the average amount of memory required by a player was 1.2 and 5.9 megabytes, respectively.

4 CONFIGURATION PLANNER

From Table 4, VARB and FIXB result in a high latency time, waste storage space, and require significant amount of memory. However, these limitations are not because of the techniques themselves, but due to their use of vendor specified physical zone configuration. A configuration planner can logically manipulate the number of zones and their specifications (e.g., by merging or eliminating zones) to resolve these limitations. For example, if it is acceptable to waste 40% of disk storage by an application (that is, its working set fit in the remaining 60%), then the planner can eliminate the innermost zones with the lowest transfer rates and treat the rest as a single zone. The transfer rate of this zone is determined by the slowest participating zone[6]. With this zone arrangement, the Seagate disk can support a maximum of 17 simultaneous displays of MPEG-1 streams by employing 21 MB of memory with a 6.86 second maximum latency time. This is superior to both FIXB and VARB (compare these numbers with the last row of Table 4). An alternative superior zone arrangement would merge zones 0 to 4 into one group, 5 to 12 in to a second group, and eliminate zones 13 to 23. With this configuration (employing VARB) and assuming $\mathcal{N} = 17$, the system will observe almost the same latency time (6.5 s) with a lower memory requirement (10 MB). The bandwidth provided by this arrangement can support up to 18 MPEG-1 displays. Another advantage of this organization is that it wastes 35% of disk storage (as compared to 40% with the other two organizations). A more intelligent arrangement might even outperform this one. Note that the definition of *outperform* depends on the requirements of an application.

Alternative applications have different performance objectives. It may not always be desirable to incur a high latency to support a large number of displays. For examples, an application might desire fewer displays in favor of a lower latency time. Hence, it might be beneficial to combine some zones (reduce m) to reduce the latency time. This would reduce the average transfer rate of each disk, reducing the number of simultaneous displays supported by the system. Another application with a very small working set might require a high throughput and a low latency time. If the working set of this application fits in the outermost zone of the disk then the system should eliminate all the other zones, harnessing the highest transfer rate for this application. By eliminating $m - 1$ zones, the incurred latency is also minimized. These examples motivate the need for a configuration planner that logically manipulates the zoning characteristics of a disk to satisfy the performance objectives of a target application.

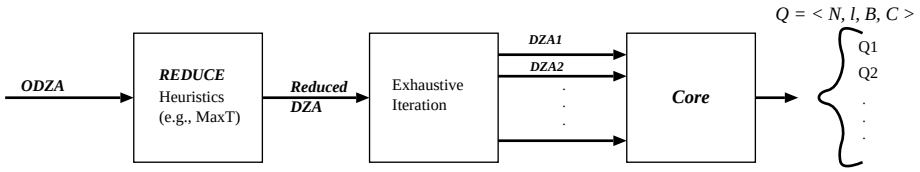
[6]This is identical to Min-Z-tfr, except that some of the inner zones are eliminated.

The inputs to the planner include the characteristics of an application, its performance objectives, and the physical attributes of the target disk drive. The characteristics of an application include $\mathcal{R}_C$ and the size of its working set. The performance objectives of the application include its desired latency ($\ell_{desired}$) and throughput ($\mathcal{N}_{desired}$). The physical attributes of a disk include: T_{W_Seek}, T_{cseek}, and its *Disk Zone Arrangement* (DZA). The outputs of the planner are a new DZA and an appropriate block size that satisfies the performance objectives while minimizing cost. A new DZA can be constructed by: 1) merging one or more adjacent zones into one, termed *merge*, 2) eliminating one or more zones from consideration, termed *eliminate*, 3) splitting a zone into several zones, termed *split*, and 4) a combination of the first three techniques. The planner consists of three components. The first component constructs all possible DZAs using a combination of merge and eliminate. A second component, termed core, computes the possible throughput, latency, memory requirement, and costs of using a DZA with either FIXB or VARB. It employs the analytical models of Section 3 for this computation. One can employ these two components to find the cheapest configuration that supports the performance objectives of an application (i.e., $\ell_{desired}$ and $\mathcal{N}_{desired}$). However, as described later in Section 4.2, the number of possible DZAs becomes large when a disk consists of a large number of zones, requiring years of computation to complete this exhaustive search. As a solution, the third component of the planner introduces heuristics. Two classes of heuristics are described: 1) REDUCE: these heuristics construct a new DZA, termed *Reduced DZA*, that consists of fewer zones than the original DZA, that is used as input to the first component of the planner (see Figure 3a), and 2) BYPASS: these heuristics eliminate the first component of the planner altogether by producing a select number of DZAs based on the knowledge of target application (see Figure 3b). In the following, we describe each of these components starting with the core. The planner is validated using MITRA in Section 4.4.

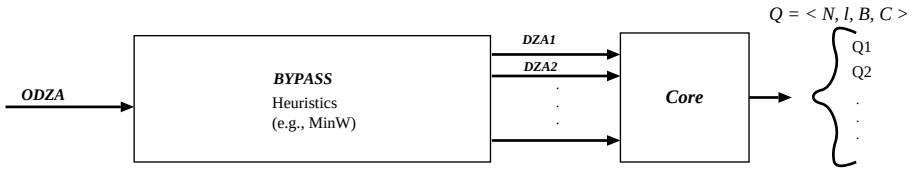
4.1 The Core

The input parameters of core are similar to those of the planner (see Figure 4). Core employs the analytical models of Section 3 to output possible values of $\mathcal{N}$, ℓ, $\mathcal{B}$, and $\mathcal{C}$ (for either FIXB or VARB). It iterates over possible values of $\mathcal{N}$ to generate these quadruples. The lower and upper bound for $\mathcal{N}$ are $\mathcal{N}_{desired}$ and $\lfloor \frac{\mathcal{R}(Z_0)}{\mathcal{R}_C} \rfloor$, respectively. $\mathcal{C}$ denotes the cost of the system. It is computed as a function of the amount of memory (Mem) required by the target application:

$$\mathcal{C} = (Mem \times \$ram) + \$disk \tag{1.8}$$



a. Class of REDUCE heuristics



b. Class of BYPASS heuristics

Figure 3 Two alternative classes of heuristics

where $ram is the cost of memory per megabyte, and $disk is the cost of the single disk drive required by the application.

The amount of wasted disk space (W) is used for two purposes. First, it is used to eliminate those DZAs that prevent the working set of an application from becoming disk resident; $size(WS) \geq cap - W$, where $size(WS)$ and cap denote the size of the working set and the disk storage capacity, respectively. Second, the waste is used to compute the extra latency time observed by requests referencing objects that do not constitute the working set of the target application. The larger the waste, the higher the probability that a reference to a non-working set object is directed to the tertiary storage device, resulting in a higher average latency time. To compute the extra latency, we use the average size of an object ($Size_{Avg\_req}$) to estimate the number of objects that constitute the database ($\#(DB) = \lfloor \frac{size(DB)}{Size_{Avg\_req}} \rfloor$) and the working set ($\#(WS) = \lfloor \frac{size(WS)}{Size_{Avg\_req}} \rfloor$). Thus, the number of objects that do not constitute the working set is $\#(DB) - \#(WS)$. A DZA may enable a larger number of objects than #(WS) to become disk resident, termed #(DZA). #(DZA) must be greater than or equal to #(WS). Otherwise, it would have been eliminated. Let #(REM) denote $\#(DZA) - \#(WS)$. Let p_1 be the probability that a request references objects inside the working set. Assuming that references

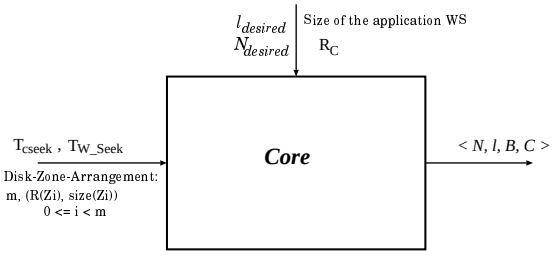


Figure 4 Core, the analytical models of the planner

are randomly distributed across the objects that constitute the portion of the database excluding its working set, the probability that a reference to one such object is directed to tertiary is $p_{ter} = 1 - \frac{\#(REM)}{\#(DB)-\#(WS)}$. Thus, the probability that a request retrieves data from the tertiary is $(1-p_1) \times p_{ter}$. It will observe a minimum extra latency time of $\frac{Size_{Avg\_req}}{D_{Tertiary}}$, where $D_{Tertiary}$ is the transfer rate of the tertiary storage device. Multiplying these components with one another, the extra latency time observed due to the wasted space is computed as:

$$(1 - p_1) \times (1 - \frac{\#(REM)}{\#(DB) - \#(WS)}) \times \frac{Size_{Avg\_req}}{D_{Tertiary}} \tag{1.9}$$

Core's output is a number of quadruples $Q =< \mathcal{N}, \ell, \mathcal{B}, \mathcal{C} >$, where $\mathcal{C}$ is the cost (computed using Eq. 1.8), and $\mathcal{B}$ either denotes block size with FIXB or the largest block size (corresponding to the outermost zone) with VARB[7]. Note that the latency time (ℓ) incorporates both latency times computed in Eqs. 1.2 and 1.9.

One can invoke Core using alternative input DZAs to generate a list of quadruples. Subsequently, a search procedure can traverse the list to locate a quadruple $Q =< \mathcal{N}, \ell, \mathcal{B}, \mathcal{C} >$, that is both the cheapest in the list (i.e., has the minimum $\mathcal{C}$ value), and satisfies the following conditions: $\mathcal{N}_{desired} \leq \mathcal{N}$ and $\ell_{desired} \geq \ell$.

[7]The block size for any zone Z_i can then be computed as $\mathcal{B}(Z_i) = \frac{\mathcal{B}}{\mathcal{R}(Z_0)} \times \mathcal{R}(Z_i)$.

Zone #	Size (MB)	Transfer Rate (MB/s)
0	140.0	4.17
1	67.0	4.08
2	45.0	4.02
3	46.0	3.97
4	44.0	3.88
5	42.0	3.83
6	41.0	3.74
7	95.0	3.60
8	37.0	3.50
9	52.0	3.36
10	35.0	3.31
11	34.0	3.22
12	46.0	3.13
13	32.0	3.07
14	31.0	2.99
15	42.0	2.85
16	55.0	2.76
17	37.0	2.62
18	25.0	2.53
19	34.0	2.43
20	20.0	2.33

Table 5 Pre-processed zone information of Seagate ST31200W disk.

4.2 Exhaustive Iteration

The input to Core is one possible DZA. The vendor-based zone configuration is the original DZA, termed ODZA. If i physically adjacent zones of the ODZA provide an identical transfer rates, then these i zones are reduced into one. The size of this zone is the total size of the i zones. For example, in Table 1b, $\mathcal{R}(Z_7) = \mathcal{R}(Z_8) = 3.60$ MB/s. These two zones are combined to form a single zone whose size is equivalent to $size(Z_7) + size(Z_8)$ and a transfer rate of 3.60 MB/s. This process is also repeated for Z_{17} and Z_{18}. Therefore, the ODZA of the Seagate disk drive of Table 1 is reduced to that of Table 5 with 21 zones.

Other DZAs can be constructed by using the following two operations: *eliminate* and *merge*. As suggested by its name, the *eliminate* operation simply eliminates zone(s) from a disk drive. Figure 5a illustrates an ODZA of a 4-zone disk drive. Figure 5b shows one possible DZA by eliminating zone 2. Zone elimination wastes disk space, however, it might increase the average transfer rate of a disk drive (e.g., if the innermost zone is eliminated). If the working set of an application requires the entire storage capacity of a disk, eliminating zones might not be appropriate because it would increase the frequency of access to the tertiary storage device. Another drawback of eliminating a zone,

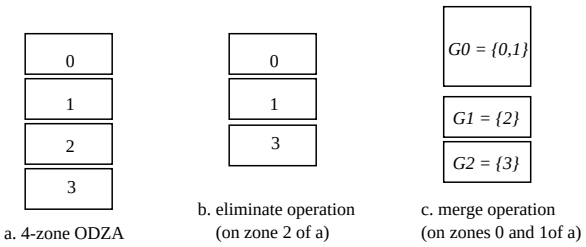


Figure 5 Eliminate and merge operations

not as significant as the wasted space factor, is the increase in T_{W_Seek} when retrieving two blocks from adjacent zones (see Section 2).

The *merge* operation combines two adjacent zones into one. Figure 5a illustrates an ODZA of a 4-zone disk drive. Figure 5c shows one possible DZA by merging zones 0 and 1. The new DZA can be considered as a disk drive with three zones ($m' = 3$). First group ($\mathcal{G}_0$) consists of Z_0 and Z_1 ($\mathcal{G}_0 = \{0, 1\}$), the second group corresponds to Z_2, and the third to Z_3. To guarantee a continuous display, the transfer rate of the group is determined by the minimum transfer rate of its constituting zones. For example, for this DZA the transfer rate and size of $\mathcal{G}_0$ is computed as following: $\mathcal{R}(\mathcal{G}_0) = \mathcal{R}(Z_1)$; $size(\mathcal{G}_0) = size(Z_0) + size(Z_1)$. Merging reduces the total number of zones (i.e., $m' \leq m$) in a DZA, resulting in a lower latency time (see Eq. 1.2). However, it reduces the average transfer rate of the disk that might result in a fewer number of simultaneous displays. It also increases T_{W_Seek}.

Using *merge* and *eliminate*, a number of DZAs can be constructed. Subsequently, each DZA can be fed to Core to generate a list of quadruples. When m is small, it might be worthwhile to generate all possible DZAs because the planner is invoked once at system configuration time. To generate all possible DZAs, first the *eliminate* operation is invoked on the ODZA, constructing all subsets (excluding the empty set) of the original set of zones. The number of possible n-element DZAs is[8]: $\left(\begin{array}{c} m \\ n \end{array} \right)$. For each DZA generated by *eliminate*, we then consider all possible *merge* operations. In general, the number of g-group DZAs that can be derived using a DZA consisting of m' zones is computed

[8]This is a *combinatorial function* (the *binomial coefficient*) which can be written as $\left(\begin{array}{c} m \\ n \end{array} \right) = \frac{m!}{n!(m-n)!}$.

as: $\begin{pmatrix} m'-1 \\ g-1 \end{pmatrix}$. Therefore, the total number of possible DZAs is computed as:

$$P = \sum_{z=1}^{m} \sum_{s=0}^{z-1} \begin{pmatrix} m \\ z \end{pmatrix} \times \begin{pmatrix} z-1 \\ s \end{pmatrix} \tag{1.10}$$

Note that the order of invoking operations (*eliminate* followed by *merge*) is important. If the order is reversed, then duplicate DZAs are produced. In this case, P' is computed as:

$$P' = \sum_{s=0}^{m-1} \sum_{z=1}^{s+1} \begin{pmatrix} m-1 \\ s \end{pmatrix} \times \begin{pmatrix} s+1 \\ z \end{pmatrix} \tag{1.11}$$

where $P' \geq P$. The states counted by $P' - P$ are duplicates. Obviously, considering duplicate DZAs wastes time.

Assume that feeding each DZA to Core and generating a quadruple requires 20 milliseconds. Traversing the entire search space to locate an optimal configuration with the 8 zone HP disk drive (see Table 1a) requires 65.6 seconds. However, this becomes a 3.3 year computation with the 21 zone Seagate disk drive because of its large number of zones that results in an explosion of possible states. This motivates the need for heuristics to reduce the number of possible DZAs.

4.3 Heuristics

The planner employs two alternative approaches to minimize the number of possible DZAs. One approach is to use heuristics to reduce the number of zones (m) in order to prune the number of possible DZAs, termed *class of REDUCE heuristics*. The reduced ODZA is used as input to the exhaustive iteration of Section 4.2 (see Figure 3a). An alternative approach is to bypass the exhaustive iteration all together, termed *class of BYPASS heuristics*. This approach selectively chooses a small number of DZAs that are used as input to the core (see Figure 3b).

A large number of heuristics can be developed for each class. A heuristic might be designed with different objectives: minimize latency, maximize throughput, minimize wasted space, etc. In this chapter we describe two. The first is a member of REDUCE that attempts to maximize the throughput of the system, termed $MaxT$. The second heuristic is a member of BYPASS that attempts to minimize the amount of wasted space, termed MinW. We describe each heuristic in turn.

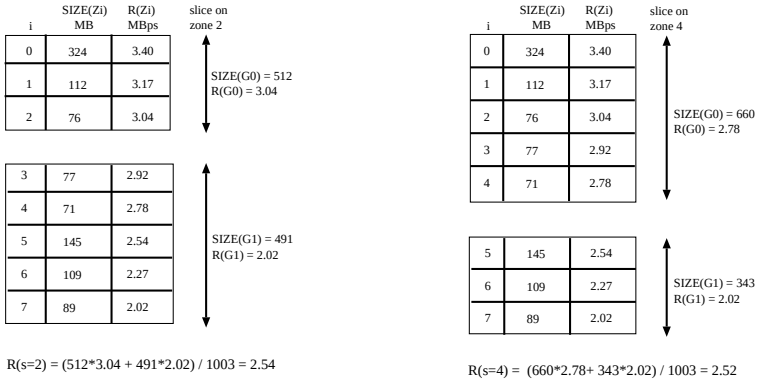


Figure 6 MaxT algorithm for $m_{desired} = 2$

MaxT Heuristic

The inputs to MaxT are: 1) the original DZA of the disk with m zones, and 2) the desired number of zones for the output DZA, $m_{desired}$, where $m_{desired} < m$. The output of MaxT is a reduced DZA that consists of $m_{desired}$ zones. For this transformation, MaxT employs the *merge* operation. Its goal is to produce a $m_{desired}$-zone DZA with a maximum expected transfer rate hoping that this would increase throughput. To compute the expected transfer rate, let us define the probability of data residing on Z_i as[9]:

$$P_i = \frac{size(Z_i)}{cap} \tag{1.12}$$

Hence, the expected transfer rate of a m-zone ODZA is defined as:

$$\mu = \sum_{i=0}^{m-1} P_i \times \mathcal{R}(Z_i) \tag{1.13}$$

Recall that merging reduces the expected transfer rate of the disk drive because the transfer rate of a group is determined by the minimum transfer rate of its constituting zones. Fixing the value of $m_{desired}$, there are several ways to merge zones of a DZA. MaxT is interested in the one that maximizes the

[9]One might argue that this probability should be based on the number of blocks accommodated by both a zone and the disk. This is infeasible because at this stage the size of a block is unknown (the size of a block is determined by the Core).

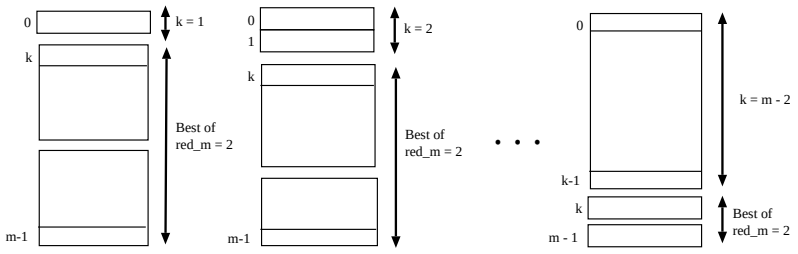


Figure 7 MaxT algorithm for $m_{desired} = 3$

expected transfer rate. To observe, consider Figure 6 where $m_{desired} = 2$. Two alternative ways of merging are demonstrated: dividing the zones into two groups by slicing the ODZA at zone 2 ($s = 2$) and 4 ($s = 4$). The expected transfer rate for constructing groups by slicing at zone k is computed as:

$$\bar{\mathcal{R}}(s = k) = \frac{\sum_{i=0}^{m_{desired}-1} size(\mathcal{G}_i) \times \mathcal{R}(\mathcal{G}_i)}{cap} \tag{1.14}$$

From Figure 6 and by applying Eq. 1.14, we obtain $\bar{\mathcal{R}}(s = 2) = 2.54$ MB/s and $\bar{\mathcal{R}}(s = 4) = 2.52$ MB/s. MaxT varies k from 0 to $m - 2$ to find a k' which maximizes $\bar{\mathcal{R}}(s = k)$.

Now assume $m_{desired} = 3$. In this case, MaxT works as depicted in Figure 7. It constructs one group by merging the first k zones. Next, it determines the best way to generate two groups using the remaining $m - k$ zones. To accomplish this, it re-invokes MaxT on a DZA consisting of zones k to $m - 1$, where $m_{desired} = 2$. This can be repeated recursively based on any value for $m_{desired}$. In general, the MaxT algorithm simulates the divide-and-conquer algorithm.

MinW Heuristic

The input to MinW is an ODZA. Its output is a number of DZAs. MinW constructs the output DZAs with the objective to reduce the amount of wasted space with either FIXB or VARB. To simplify the discussion we first describe this heuristic for FIXB.

MinW is based on the observation that the zone with the minimum size determines the total useful capacity of a disk drive. By forcing the zones to be equi-sized, MinW can minimize the wasted space. The *split* operation (see Figure 8) partitions a zone (say Z_i) into two or more equi-sized sub-zones. The

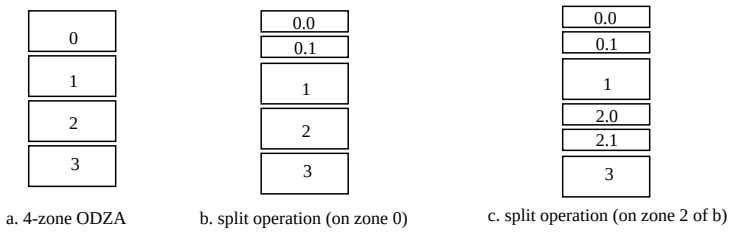


Figure 8 Split operation

transfer rate of each sub-zone is identical to the transfer rate of Z_i. This increases the number of zones in a DZA[10]. However, by constructing equi-sized zones, the percentage of wasted space with FIXB is reduced.

To construct equi-sized zones, one can force the size of each sub-zone to be the GCD (Greatest Common Divisor) of the possible zone sizes. Subsequently the GCD is considered as the size of each sub-zone, termed *subsize*, and each zone i is splitted into $\frac{size(Z_i)}{subsize}$ sub-zones. This approach raises two issues. First, the zone sizes are real numbers in Megabytes, while GCD is meaningless for real numbers. Second, if at least two of the zone sizes are prime numbers, then their GCD will be 1 (i.e., $subsize = 1$), resulting in a large number of zones. There are two solutions for the first problem: 1) consider lower units (such as Kilobytes) for the zone sizes in order to convert them to integers, and/or 2) truncate the sizes and suffer from some *internal fragmentation*. To solve the second problem, we vary *subsize* from the GCD to the size of the smallest zone[11]. When $subsize \neq$ GCD, some space is wasted per zone because $\frac{size(Z_i)}{subsize}$ might not be an integer number. We term this waste *external fragmentation*. MinW generates one DZA per value of *subsize*. Subsequently, for each DZA it computes the waste (resulting from both internal and external fragmentation) and the number of zones. In practice, we vary *subsize* from the size of the smallest zone **down-to** the GCD. As *subsize* approaches the GCD, the number of zones increases. However, the amount of waste might either increase or decrease. MinW maintains only those DZAs with few zones that minimize waste.

The complexity of MinW for FIXB is $O(cap)$. This is because for each value of *subsize*, MinW traverses all the m zones to apply the *split* operation. Moreover,

[10] This explains why *split* is not appropriate for use in the REDUCE class of heuristics.

[11] To force the sub-zones to be equi-sized, *subsize* should not exceed the size of the smallest zone.

the number of possible *subsizes* is $\frac{cap}{m}$. This is assuming the worst case of GCD = 1 and the size of the smallest zone being $\frac{cap}{m}$. Due to this complexity ($O(\frac{cap}{m} \times m) = O(cap)$), assuming Kilobytes as disk storage capacity might result in a long computation time. Hence, choosing a unit for storage capacity is a trade-off between minimizing the internal fragmentation as compared to reducing both the computation time of the algorithm and the number of resulting zones.

The algorithm of MinW for VARB is similar to that of FIXB. The difference is that the zones should be forced to have a fixed $\frac{size(Z_i)}{\mathcal{R}(Z_i)}$ in order to minimize the waste. Therefore, the GCD is computed for the size over transfer rate of zones. Furthermore, a $rate\_factor$ is varied from the minimum value of $\frac{size(Z_i)}{\mathcal{R}(Z_i)}$, where $0 \leq i < m$, down to the GCD. Subsequently, the size of the Z_i's sub-zones ($subsize(Z_i)$) is computed as: $subsize(Z_i) = rate\_factor \times \mathcal{R}(Z_i)$. The complexity of this algorithm is $O(\frac{cap}{\mu})$, where μ is the expected transfer rate of the disk (see Eq. 1.13).

In Section 5, we show that MinW enables VARB to waste no space of the HP disk by increasing its number of zones to 14 and fixing $\frac{size(Z_i)}{\mathcal{R}(Z_i)}$ at 21 seconds. However, the internal and external fragmentation caused by the *split* operation wastes 18% of the disk space. One might be tempted to apply the exhaustive iteration on the obtained 14-zone DZA. This is not recommended because the exhaustive iteration might destroy the fixed value of $\frac{size(Z_i)}{\mathcal{R}(Z_i)}$. This also explains why MinW is considered as a BYPASS instead of a REDUCE heuristic.

4.4 Validation of the Planner

Similar to Section 3.4, we employed MITRA to verify the configuration planner. The obtained results demonstrate that one can strike a compromise between the throughput and latency time of a disk drive by logically manipulating zones.

In the first experiment, we employed the MaxT heuristic to construct two logical zones. MaxT merged the first 12 zones of the Seagate disk into one group and the rest of the zones into another. MITRA realizes this logical organization using two file systems. The first file system spans the first 12 zones while the second spans the remaining zones. Employing the analytical models, the block size and $T_{MUX}(Z_i)$ ($0 \leq i \leq 1$) were computed to configure MITRA. With this configuration, MITRA can support up to 14 simultaneous displays with an average latency time of 0.22 seconds (as compared to an average latency of 45.423 seconds with 23 zones in Section 3.4). Similar to the discussion of

Disk Capacity cap	1 Gigabyte
Max. Rotational Latency Time	9.33 milliseconds
Max. Seek Time	10.39 milliseconds
T_{W_Seek}	9.33 + 10.39 = 19.72 milliseconds
T_{cseek}	19.39 milliseconds

Table 6 Seagate and HP disk parameters

Section 3.4, the theoretical throughput of 15 streams by the analytical models cannot be achieved due to the overheads incurred by the HP/UX operating system.

In the second experiment, we used the eliminate operation to eliminate the last 14 zones of the Seagate disk and merge zones 0 to 8 into one logical zone (Z_0). In this experiment, the size of the database is smaller than the aggregate storage space provided by these zones. With the computed system parameters (using analytical models), MITRA supports 19 simultaneous displays with an average latency of two seconds.

Section 5 evaluates other zone arrangements constructed by the planner. We did not configure MITRA for each arrangement proposed by the planner because these experiments are redundant. Both this section and Section 3.4 have already established the accuracy of proposed analytical models.

5 PERFORMANCE EVALUATION

We conducted some experiments to: 1) demonstrate the flexibility and superiority of our approach as compared to the conventional approach (Min-Z-tfr) which assumes the transfer rate of the innermost zone as the transfer rate of the disk, 2) evaluate our heuristics, and 3) compare VARB with FIXB in the presence of heuristics. For this purpose, we considered the system latency time, throughput and cost as performance criteria. The system cost is determined assuming a memory cost of $35 per MB, and $500 for a one-gigabyte disk drive. In these experiments we used both Seagate and HP disk drives (see Table 1). Except for the zoning information, the remaining parameters of these two disks are almost identical. Table 6 summarized the values of these parameters.

The target application is a news-on-demand. Its database consists of 100 MPEG-1 compressed news clips, each with a 1.5 Mb/s bandwidth requirement.

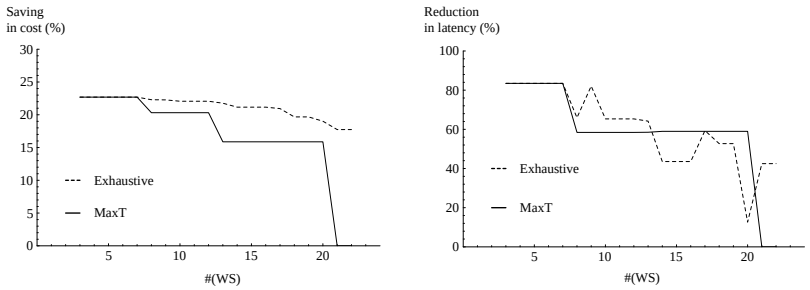
Number of objects in working set #(WS)	*Maximum number of users*				
	Min-Z-tfr, MaxT $m_d = 1$	MaxT $m_d = 3$	MaxT $m_d = 5$	MaxT $m_d = 6$	Exhaustive, MaxT $m_d = 8$
3	10	16	16	16	16
4	10	16	16	16	16
5	10	16	16	16	16
6	10	16	16	16	16
7	10	16	16	16	16
8	10	12	14	15	15
9	10	12	14	15	15
10	10	12	14	13	14
11	10	12	14	13	14
12	10	11	13	13	14
13	10	11	12	13	14
14	10	11	12	13	13
15	10	11	12	12	12
16	10	11	12	12	12
17	10	11	12	12	12
18	10	11	11	11	11
19	10	11	11	11	11
20	10	11	11	11	11
21	10	10	10	10	11
22	10	10	10	10	11

Table 7 Maximum throughput with fixed latency time ($\ell = 3.2$ sec) in HP C2247 disk (Note: m_d in this table is $m_{desired}$)

The duration of each news clip is 4 minutes. Thus each clip is 45MBytes in size, resulting in a 4.5 GBytes database. We varied the size of the working set from 3 news clips (135 MB) up to 22 (990 MB). The probability of reference to the working set objects is 95%. We assumed a tertiary storage device with a transfer rate of 0.25 MB/s.

We compared our approach with a conventional approach that assumes the disk consists of a single zone with the transfer rate of the innermost zone and the storage capacity of the entire disk (Min-Z-tfr; MaxT with $m_{desired} = 1$). In addition to considering MaxT with different $m_{desired}$ values, we also considered the full exhaustive iteration without heuristics, termed *Exhaustive*[12]. Exhaustive is identical to MaxT invoked with $m_{desired} = 8$ using the HP disk drive. Table 7 presents the maximum number of users supported by each technique (columns 2 to 6) as a function of the number of clips that constitute the working set (first column). We set $\ell_{desired}$ at the one observed with Min-Z-tfr, 3.2 seconds. The throughput with Min-Z-tfr is independent of the size of the working set because it wastes an insignificant fraction of the disk space (i.e., utilize almost 100% of the disk space). When $size(WS) \leq 900$ MB, MaxT and

[12] We can consider the entire search space for the HP disk because it consists of eight zones.



a. Cost b. Latency

Figure 9 Latency time and system cost with HP disk ($\mathcal{N} = 10$, $m_{desired} = 3$ for MaxT)

Exhaustive construct a DZA that results in a higher throughput as compared to Min-Z-tfr. When $size(WS) > 900$ MB, Exhaustive chooses a DZA that logically consists of two zones with an average transfer rate that can support 11 displays, outperforming Min-Z-tfr. Note that a larger value for $m_{desired}$ does not always translate into a higher throughput, For example, when the working set consists of ten clips (8^{th} row of Table 7), MaxT with $m_{desired} = 6$ results in a lower throughput when compared with $m_{desired} = 5$. This is because MaxT is only a heuristic and might fail to compute an optimal throughput. This also explains why Exhaustive outperforms MaxT. Similar observations were made with the Seagate disk drive (see Appendix A.2).

We considered the minimum cost configuration that supports the latency and throughput identical to that provided by Min-Z-tfr. Figure 9a shows the percentage reduction in cost obtained with both Exhaustive and MaxT ($m_{desired} = 3$) relative to Min-Z-tfr. This percentage is computed as $(1 - \frac{cost(Exhaustive)}{cost(Min-Z-tfr)}) \times 100$ and may not exceed 100%. Exhaustive provides a more significant saving when compared to MaxT because it considers all possible DZAs. The cheapest configuration does not necessarily minimize the latency time. Figure 9b shows the percentage reduction in latency with both Exhaustive and MaxT relative to Min-Z-tfr. While Exhaustive minimizes cost, it also results in a higher average latency for some working set sizes. Relative to Min-Z-tfr, both Exhaustive and MaxT provide a significant reduction in latency for small working set size.

MinW is insensitive to the working set size. This is because it avoids the *merge* and *eliminate* operations all together. It cannot outperform Exhaustive

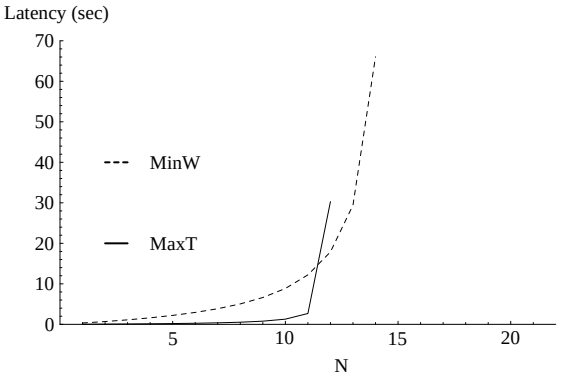


Figure 10 MinW vs. MaxT ($size(WS)$ = 810 MB)

Number of zones (m)	disk storage waste (%)	latency (sec)
14	18	60.6
16	14	62.0
26	12	108.3
30	8	126.9
42	6	174.6
69	3	257.9
175	2	711.9

Table 8 MinW heuristic ($\mathcal{N} = 14$)

because in the worst case Exhaustive simulates Min-Z-tfr which results in no waste. However, for large working sets where the amount of waste should be minimized, MinW outperforms MaxT. This is demonstrated in Figure 10 where the size of the working set is fixed at 810 MBytes and $\mathcal{N}$ is varied. MinW can support a higher number of displays because it employs the average transfer rate of the disk by splitting zones. MaxT constructs a DZA with one zone to accommodate the large working set, assuming the minimum transfer rate of the disk.

Table 8 demonstrates the number of zones constructed by MinW and its impact on both the percentage of wasted space and latency. The reported numbers are based on the maximum number of displays supported by MinW, $\mathcal{N} = 14$. Observe the tradeoff between latency and percentage of wasted space. A higher

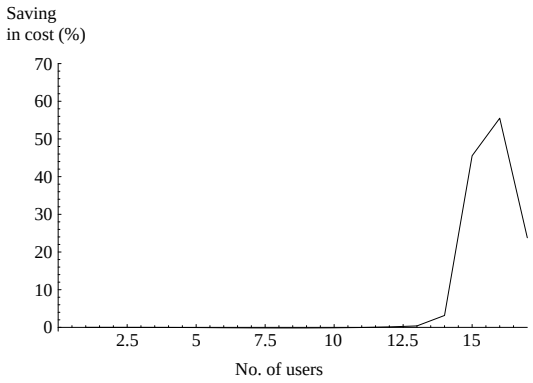


Figure 11 Cost comparison between VARB and FIXB ($size(WS)$ = 315 MB,ℓ = 30 sec)

number of zones minimizes the wasted space at the expense of a higher latency time.

Finally, we compared FIXB and VARB in the presence of heuristics. Figure 11 summarizes the obtained results. The x-axis of this figure is the desired throughput and the y-axis is the percentage of saving in the system cost for VARB as compared to FIXB ($\frac{cost(FIXB)-cost(VARB)}{cost(FIXB)}$). The size of the working set and the latency time were fixed at 315 MB and 30 seconds, respectively. We employed MaxT for the HP disk drive with $m_{desired} = 3$. Since FIXB requires a larger memory to satisfy a higher throughput, it costs more when the number of active users is higher than 13. These results are in accordance with the observations of Section 3.3.

6 MULTI-DISK PLATFORM

The bandwidth of a single disk is insufficient for those applications that strive to support thousands of simultaneous displays. One may employ a multi-disk architecture for these applications. Assuming a system with D homogeneous disks, the data is striped [2, 11, 13] across the disks in order to distribute the load of a display evenly across the disks. Striping realizes a scalable server that can scale as a function of additional resources. The striping technique is as follows. First, we partition the disks into k disk clusters each with d disks: $k = \lceil \frac{D}{d} \rceil$. With each object X partitioned into f blocks (X_0, X_1, ..., X_{f-1}), we

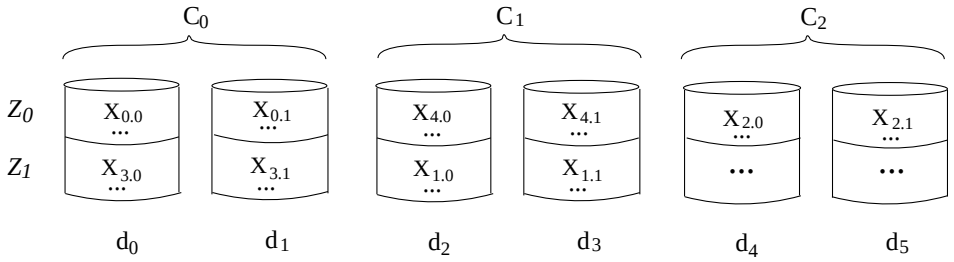


Figure 12 Three clusters with two logical zones per cluster

assign the blocks of X to the disk clusters in a round-robin manner, starting with an arbitrarily chosen disk cluster and zone (say zone Z_j of disk cluster C_i). The remaining blocks of X are assigned to the zones and disk clusters in a round-robin manner. Assuming that each disk consists of m logical zones, block X_1 is assigned to zone $Z_{(j+1) \ mod \ m}$ of disk cluster $C_{(i+1) \ mod \ k}$. In a cluster, each block of X is declustered [14] into d fragments, with each fragment assigned to a different disk in a disk cluster. The system requires the fragments of a block to be assigned to the same zone of the d disks that constitute a cluster. Figure 12 shows the assignment of X to a three cluster system where each cluster consists of two logical zones.

One zone of all disks is active per time period. To display object X of Figure 12, the system must wait until zone Z_0 of disk cluster C_0 becomes active. If an idle time slot exists for this cluster, the system employs the idle slot to retrieve X_0. During the next time period, the system retrieves X_1 from zone Z_1 of disk cluster C_1. This process is repeated until all blocks of object X have been retrieved and displayed. This display paradigm is similar to the discussion of Section 3.1 except that a display visits the clusters in a round-robin manner utilizing a slot per time period in to retrieve blocks of X from different zones of the available clusters.

This assignment and display paradigm strive to distribute the load of a display evenly across the available disk clusters. However, a single cluster of a thousand cluster system might become a bottleneck depending on the number of zones, clusters, and the assumed placement of the data. This is best illustrated using an example. Assume a system whose disks consist of 3 zones. Its disks are organized into 3 clusters. Suppose that each cluster can support the retrieval of 4 blocks during a time period. Assume that the assignment of the first block of each object starts with zone Z_0 of disk cluster C_0. An immediate

ramification of this assignment technique is that the storage capacity of the three cluster system is equivalent to that of a single cluster because no blocks are assigned to: zones Z_1 and Z_2 of cluster C_0, zones Z_0 and Z_2 of cluster C_1, and zones Z_0 and Z_1 of cluster C_2. Moreover, the system cannot support more than four simultaneous retrievals. To illustrate, if 12 requests arrive referencing different objects, they all map to zone Z_0 of cluster C_0. Four of these requests become active during the first time period. During the second time period, these four requests proceed to zone Z_1 of disk cluster C_1. The remaining 8 requests remain queued because their referenced zone is Z_0 and this zone is inactive. Everytime zone Z_0 becomes active, none of the pending requests can be activated because the available time slots are exhausted. The retrieval of data on behalf of a pending request starts when one of the four active requests completes its retrieval (relinquishes a time slot) and zone Z_0 becomes active.

It is interesting to note that there can be multiple bottleneck clusters. To illustrate, if our example system consists of 6 clusters (instead of 3) then there would be 2 bottleneck clusters in the presence of more than 8 requests (clusters C_0 and C_3). (Note that with these parameters the available storage capacity of the system is twice, i.e., $\frac{k}{m}$, that of a cluster.) In this example, the probability of two clusters becoming bottlenecks for the entire system is 100%. One can minimize this probability by assigning the blocks of each object starting with a random cluster and random zone. However, the system continues to run the possibility of a bottleneck cluster either when the number of clusters is a multiple of zones ($k \geq m$) or when the number of zones is a multiple of clusters ($k \leq m$). In the first case ($k \geq m$), $\frac{k}{m}$ of clusters may become bottlenecks. In the latter ($k \leq m$), a single cluster becomes a bottleneck.

One way of preventing bottlenecks is to avoid system configurations where either (1) k is a multiple of m or (2) m is a multiple of k. The configuration planner of Section 4 can be extended with heuristics to incorporate these system configurations. Assuming that such configurations are avoided, for a fixed cluster size (fixed value of d) and logical zones, as one increases the number of disk clusters (k), the throughput, maximum startup latency, and the amount of memory required by both FIXB and VARB increase linearly. With a single disk cluster, as one increases the number of disks in a cluster (d), the throughput of the system increases linearly while the amount of required memory and the incurred startup latency increases super linearly. These observations were made by [13, 22] for a multi-disk architecture assuming a single zone. The extension of these observations for multiple zones is a trivial extension of these studies using the analytical models of Section 3.

7 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This chapter describes two techniques that ensure a hiccup-free display of continuous media data types using a multi-zone disk drive. As compared to the previous studies, the proposed techniques strive to maximize the transfer rate observed from each disk drive instead of assuming their minimum transfer rate. We described a configuration planner that consumes the performance criteria of an application and logically configures the active zones of a disk drive to support the desired criteria of the application. Due to the large size of this optimization space, Section 4 introduced heuristics to speedup the planner. Our experimental results (Section 5) demonstrate the superiority of the proposed techniques when the working set of an application does not require the entire storage capacity of the disk drive.

We are extending the proposed designs in two ways. First, we are exploring the role of objects that require variable bit rate for their display. In this case, the schedule of retrieval become challenging. Second, we are analyzing databases that consist of a mix of media types, each with a different bandwidth requirement and performance criteria. Given such a mix, the block size and zone configuration should be chosen to strike a compromise for the alternative media types.

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APPENDIX A

$\mathcal{N}$	*FIXB*	*VARB*		
	Block Size (MBytes)	Minimum Block Size (MBytes)	Maximum Block Size (MBytes)	Average Block Size (MBytes)
1	0.0043	0.0031	0.0053	0.0043
2	0.0088	0.0064	0.0108	0.0088
4	0.0204	0.0147	0.0248	0.0202
8	0.0653	0.0461	0.0776	0.0632
10	0.1187	0.0816	0.1374	0.1118
11	0.1692	0.1136	0.1911	0.1556
12	0.2623	0.1686	0.2838	0.2310
13	0.4918	0.2862	0.4817	0.3921
14	1.9752	0.7133	1.2006	0.9773

Table A.1 Hewlett-Packard C2247 disk

$\mathcal{N}$	*FIXB*				*VARB*			
	Mem. (MB)	ℓ (Sec)	% wasted disk space	% Avg wasted band.	Mem. (MB)	ℓ (Sec)	% wasted disk space	% Avg wasted band.
1	0.007	0.18	43.3	93.0	0.008	0.18	44.8	93.2
2	0.023	0.37	43.3	86.0	0.029	0.37	44.8	86.4
4	0.097	0.86	43.3	72.1	0.125	0.86	44.8	72.8
8	0.670	2.78	43.4	44.3	0.754	2.69	44.8	45.7
10	1.601	5.06	43.3	30.3	1.655	4.77	44.8	32.2
11	2.575	7.21	43.4	23.4	2.525	6.63	44.9	25.4
12	4.468	11.19	43.5	16.4	4.080	9.85	44.9	18.6
13	9.308	20.98	43.5	9.5	7.487	16.73	44.9	11.9
14	41.289	84.27	44.8	2.5	20.05	41.69	45.4	5.1

Table A.2 Hewlett-Packard C2247 disk

A.1 FIXB VS VARB FOR HP C2247 DISK

This section contains a comparison of FIXB and VARB for the HP disk drive. The observations from these tables are almost identical to those of Section 3.3 and not repeated. One difference is the lower percentage of wasted disk space with FIXB as compared to VARB. This is attributed to the physical characteristics of the zones on the HP disk drive.

A.2 MAXIMUM THROUGHPUT FOR SEAGATE ST31200W DISK

This appendix contains the experimental results of Section 5 using the Seagate disk drive. The observations from Table A.3 is identical to those of Section 5.

Number of objects in working set #(WS)	*Maximum number of users*				
	Min-Z-tfr, MaxT $m_{des.} = 1$	MaxT $m_{des.} = 3$	MaxT $m_{des.} = 6$	MaxT $m_{des.} = 8$	MaxT $m_{des.} = 12$
3	12	18	20	20	20
4	12	18	20	20	20
5	12	18	20	20	17
6	12	18	16	16	17
7	12	18	16	16	17
9	12	18	16	16	16
10	12	16	13	14	16
12	12	16	13	14	16
15	12	16	13	14	16
16	12	16	13	14	15
17	12	15	13	14	15
18	12	14	13	14	14
19	12	12	13	14	14
20	12	12	13	13	13
22	12	12	12	12	12

Table A.3 Maximum throughput with fixed latency time ($\ell = 7.8$ sec) in the Seagate ST31200W disk

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