AC-BPFS: A File System for Tiered Storage

Aishwarya Ganesan
ag@cs.wisc.edu

Saket Saurabh
ssaurabh@cs.wisc.edu

Siddharth Suresh
siddharth@cs.wisc.edu

Udip Pant
upant@cs.wisc.edu

Abstract

Fast non-volatile memories (NVM) are byte addressable, offer latencies close to DRAM and have densities better than DRAM that allow applications to persist their data close to memory latencies, but at a higher predicted cost per byte. The I/O latency of a disk-based filesystem is higher than a pure memory-based filesystem, but memory-based filesystems are limited by their storage cost. We propose a hybrid approach, where we use NVM as a primary storage and flash/disk as secondary storage. This paper provides the design and implementation of a file system for a persistent storage tier that includes both NVM and disks.

1 Introduction

Most modern systems have been built with the disk or SSDs as the persistent storage medium and the DRAM for temporary fast byte-addressable memory usage. The data that resides in volatile memory can be lost on crashes or power failure. Moreover, with the emergence of modern storage technologies and new byte addressable persistent memory technologies which offer much lower write and read latencies compared to flash memory at a slightly higher cost, it is imperative that future systems would move towards the usage of byte-addressable non volatile memory (Non Volatile Memory) as the primary storage with the disk as the secondary storage medium. There has always been a trade-off between data durability and data read/write performance when deciding between a fast, volatile storage medium like DRAM versus a slow, persistent storage medium like disk. Persistent memory technologies like phase change spin-torque transfer RAM (STT-RAM), phase change memory (PCM), resistive RAM (ReRAM), and 3D XPoint memory technology can solve both of these problems.

One of the earliest file systems to be proposed for non-volatile memory systems was the byte-addressable persistent file system (BPFS) [5] by a group of researchers working at Microsoft Research. [5] showed that simply running a disk-based traditional file system on top of persistent memory is not enough to provide high performance. It proposes a tree based data structure to store the file system meta data and also assumes that the hardware is capable of providing in place atomic updates of 8 bytes. A new technique called short-circuit shadow paging has been introduced to perform consistent updates to metadata, which is similar to the copy-on-write. BPFS achieves fine-grained access to persistent data at a much improved performance, while at the same time providing strong reliability and safety guarantees. But since BPFS has been built primarily for NVM as the persistent store and the cost/byte of NVM could potentially hinder such a filesystem from being used in commodity systems that do not have sufficient NVM storage capacity and are built with disks or flash as the persistent data store. Hence, AC-BPFS builds on the existing BPFS implentation thus leveraging the benefits of BPFS, but also provides a modified file system that outperforms existing file system implementations in the presence of a storage tier that consists of both NVM and disk or flash.

Since the capacity of NVM is limited and since all data blocks cannot be stored in NVM, we have explored the usage of Anti-Caching [6] as a mechanism to move data blocks between NVM and disk. The primary motivation of using Anti-Caching is to reduce write latencies, since all writes are write-back and are persisted in NVM, but at the same time does not worsen the read performance as well, due to minimal additional overhead. An Anti-Cache

system uses memory as the primary storage and disks as the secondary storage and is designed to evict cold data actively. It has only one copy of the data, which is either in NVM or on disk. It thus entails the storage of the more frequently accessed data blocks in NVM and stores the rest of the blocks on disk or flash. In addition to Anti-Caching, we also move blocks that are read from disk to NVM. This approach is very similar to the virtual memory swapping in operating systems wherein when the amount of data exceeds available memory, cold blocks are written to disk giving an impression to the file system that the amount of memory in NVM is infinite but at the same time provides the best possible performance with the amount of NVM available.

AC-BPFS provides a flexible file system design that scales itself well irrespective of the size of the storage tier, i.e capacity of NVRAM and capacity of disk or flash. The modular implementation further permits users to modify individual components and apply different policies for anti-caching and disk management depending on the requirement. In the next few sections we will provide some background information on BPFS and anti-caching and also discuss the design and implementation of AC-BPFS in detail. Finally we evaluate the performance of AC-BPFS under various system configurations.

2 Background

In this section, we will briefly discuss the relevant background on BPFS [5], a file system for byte addressable persistent memory. BPFS is one of the earliest file systems to be proposed for non-volatile memory systems and the authors showed that simply running a disk-based traditional file system on top of persistent memory is not enough to provide high performance. We will first introduce the BPFS file system layout and also discuss why the design is limited in terms of the cost of storage and volume of storage. We will also briefly describe the techniques proposed in BPFS to achieve consistency and how they achieve atomicity and write ordering. We then describe the changes made to the persistent data structures and file system code to support a disk backed secondary storage in a subsequent section.

2.1 BPFS Layout

BPFS stores all the file system meta data and data in the form of a tree structure consisting of fixed-size blocks of 4KB in the non-volatile memory. Figure 1 depicts the file system organization in BPFS. The BPFS file system consists of three kinds of files namely inode file, directory file and data file with each of these in turn arranged as a tree. The inode file is represented by a tree structure with the root of the inode file serving as the root of the file system. The location of this root node is stored at a known location in the non-volatile memory. Each of the leaves in the inode file contains an array of inode structures with each inode structure representing either a file or a directory. This inode structure contains the pointer to the root of the file or directory that the inode represents. The leaves of a data file tree are the data blocks and the leaves of a directory file tree are the directory entries.

2.2 File System Consistency

BPFS maintains file system consistency by a technique called short-circuit shadow paging. Shadow paging is a copy on write technique, where to modify a node in the tree a copy is made and the data is written to the copy. This requires updates of indirect pointers, which in turn triggers copy on writes on these indirect pointer blocks and this bubbles up to the root of the file system. Short-circuit shadow paging is an optimization, where the byte-addressability and atomic 64-byte write guarantee provided by NVM, makes in-place updates feasible. Hence, in-place updates are performed whenever possible. Short-circuit shadow paging guarantees that file system operations will commit atomically and in program order. Ordering is provided by hardware primitive called epoch barriers. In a disk based file system, for the writes to be durable, we need to flush the operating system buffer cache. Similarly, for the data to be durable in NVM, we have to flush the CPU caches. BPFS provides the guarantee that data is made durable as soon on *fsync* operation by flushing the CPU caches.

NVM storage cost is higher and so we are limited by the available NVM size. Hence any file system built completely on NVM will be limited by the storage available. Therefore, the storage capacity of BPFS is limited.

3 Design and Implementation

Our goal is to build a file system for a tiered storage hierarchy consisting of disks and NVM that combines the low latency of NVM and low cost of disk-based storage without regressing on performance while offering similar consistency guarantees as BPFS. This seems like a reasonable goal, however, it raises the some non-trivial questions about the overall design of such a tiered filesystem:

- How do we make changes to BPFS data structures so that it is able to locate the data in-memory or disk?
- What policies determine when to move data?
- Do we handle the disks directly or do we go through another file system to store data on disk?
- What is the ideal granularity at which we should move the data?

We provide answers to these questions in this section and discuss at length, the policies and mechanisms required to implement the same. Figure 2 depicts the overall design of our system. We use NVM to store the filesystem metadata and all the filesystem operations are always done within the NVM tier. To preserve the filesystem consistency guarantees, we have opted for a simple design policy where only the data blocks are moved to the disks, while the metadata blocks always reside in the persistent NVM. Such a policy entails that for a given BPFS file, its data may be split across NVM and the disk. However, it is to be noted that even though a data block may be moved between the NVM and the disk, there will always be a single valid copy of that data block- whether in the disk or in the NVM.

The mechanism to determine the exact location of the valid copy of a given data block is through the use of the most significant bit(MSB) of the indirect pointer, pointing to the data block in the BPFS tree structure. This is also being depicted in the Figure 2. If the MSB is not set, then the rest of the 63-bits denote a memory address of the data block within the NVM itself. While on the other hand, if the MSB is set, then the rest of the 63-bits denote a disk address where the data block was moved to on the disk. This answers the first question that we had raised earlier. In the following subsections, we discuss the design

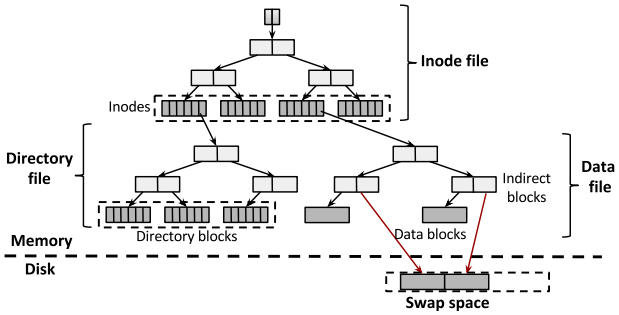


Figure 1: **BPFS tree structure.** *The figure shows the file system organization of BPFS, along with our proposed modifications.*

and implementation of Anti-Cache Manager and the Disk Manager that provide answers to the other design questions.

3.1 Anti-Cache Manager

In our design, NVM is the primary data store where all filesystem operations are being performed and hence, it contains the more frequently accessed blocks. We refer to such data residing in NVM as the 'hot' data. Since the capacity of the persistent NVM is limited, we have to periodically evict blocks from NVM to disk, so that we can make space for more 'hot' data. The evicted data on the disk is referred to as the 'cold' data. While it is true that some of the 'hot' data may become 'cold' over time, it is also possible that some 'cold' data will suddenly become 'hot' and it has to be brought back in NVM. This is what we term as the 'anti-caching' phenomenon- this gameplay between the 'hot' and the 'cold' data having a reverse caching effect. This anti-caching is at the heart of our implementation that enables us to amortize the cost of read-write operations equivalent to those provided by BPFS. We implement the well-known LRU-1 policy to distinguish the 'hot' data blocks from the 'cold' data blocks. We maintain a linked list of all the data block references. Whenever a data block is accessed, it is moved to the front of the linked list. Over time, the tail of the list will contain block references which have been least frequently accessed, while the head of the list will point to data blocks being most frequently accessed.

The Anti-Cache Manager component of the AC-BPFS filesystem implements the above proposed design policies. It runs as a separate background thread that continuously receives a stream of NVM data block references from the main AC-BPFS

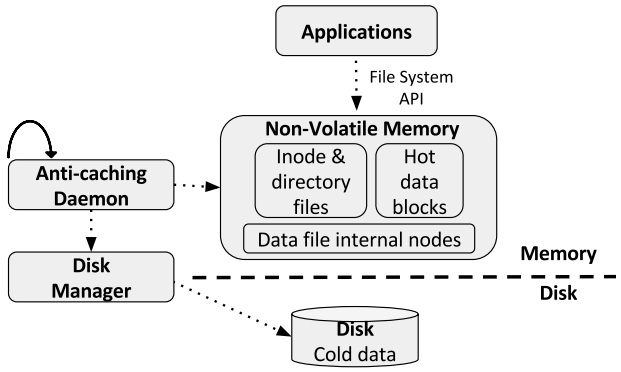


Figure 2: **Design Architecture of AC-BPFS.** *The figure shows the overall design of our system.*

thread, in the order they are being accessed. It maintains an LRU data structure within itself and uses the LRU to evict a number of blocks according to the policy explained above. A soft threshold count of data blocks, known as 'anti-caching threshold', is used to determine when and how many blocks to evict. The Anti-Cache Manager is made to poll arbitrarily every 10 ms on the size of the LRU list. If the size of the LRU list exceeds the specified anti-caching threshold of data blocks count in NVM, those many extra data blocks over the threshold are evicted from the tail of the list. This anti-caching threshold is set based on the latency of NVM writes and the polling time. We found that setting the anti-caching threshold to 80% of the NVM size for a 10 ms polling duration is a good estimate. In order to ensure that data blocks that are currently being evicted to disk do not get updated by the file system, a block level locking mechanism is used which implicitly prevents any updates to the block.

This subsection answered our second question on the policies required to move data between NVM and the disk. The next subsection gives the answers to the remaining two questions.

3.2 Disk Manager

The Disk Manager component simulates a virtual disk using a file stored on disk in the BPFS partition of a predetermined size. It exposes APIs for reading and writing blocks into the disk individually and in bulk. It performs prefetching of additional blocks when a read is performed. The lifetime of the prefetched blocks in memory is predetermined to ensure that unused prefetched blocks are cleaned up regularly with the help of a background thread. To avoid fragmentation, a free list of blocks that have been freed is maintained. Since the disk manager writes blocks to a file, the buffer cache is used to buffer writes until all the blocks are written into the file. Our current implementation provides consistency at the expense of performance by notifying BPFS after persisting the blocks, which inturn updates the indirect pointer in the inodes to point to the new blocks through a blocking call.

The disk manager also exposes another write API to the Anti-Cache Manager to facilitate writing one block at a time, for faster random writes since any free block on disk can be used for writing and does not require sequential locality. To further improve performance in the case of bulk eviction of blocks from the anti-cache manager, the disk manager performs an explicit flush only after writing all the blocks on to the disk.

3.3 File System Operations

In this section we describe the workflows for various file system operations.

3.3.1 Read

When a read operation is performed on a file, the BPFS crawls the inode tree to the indirect block containing the pointer to the data block, identifies the location of the data block using the MSB that indicates whether the block is on disk or in NVM, then fetches the block into memory and asynchronously writes it back into NVM. Once the block is persisted in NVM, it frees the block on disk and updates the indirect pointer in the inode tree to point to the new block location in NVM atomically.

When a read operation is performed on a directory, the BPFS crawls the inode tree and the directory file blocks are loaded into memory from NVM and the necessary updates are made into the directory entry cache. It then traverses all the necessary inodes in the directory file and reads them from NVM.

3.3.2 Write

When a write operation is performed on a file, the BPFS traverses the inode tree to find the indirect block containing the pointers to the data block of the file and identifies the location of the data blocks. If the data block is in NVM, the write operation is performed in-place and has no additional overhead. If the data block is on disk, the block is fetched into

NVM thus performing a copy on write of the data block and this block is updated and written back to NVM. The block on disk is then freed and the control comes back to the BPFS crawler. The indirect pointer in the inode tree is then updated to point to this new block location in-place along with in-place writes of the other internal nodes. The inode access time is also updated through an in-place atomic write.

3.3.3 Open

When a file is opened, the directory inode tree is parsed to find the file. If the file is not found and a create is requested, a new inode number is generated and the new inode is written to the inode file. Then the directory file is then updated. All these updates are performed in place. Since the metadata updates are in-place and in NVM, they are faster than usual disk writes and the additional overhead of metadata journaling can also be avoided by avoiding disk writes.

4 Evaluation

To evaluate our design and implementation, we compare the performance of the modified *AC-BPFS* on a storage hierarchy of NVM and disk with that of the original *BPFS* [5] on NVM and *ext4* (ordered mode) on disk. We use the performance of the original *BPFS* on NVM as a baseline and focus on the following key questions:

- What is the overhead of the anti-caching mechanisms implemented on top of *BPFS*?
- What is the performance of *AC-BPFS* in the presence of eviction of cold blocks?
- How does performance of *AC-BPFS* differ for various anti-caching eviction thresholds?
- How does the degree of hotness and hotness of stored data affect the performance of the system?

Hypotheses: Our hypothesis is that when accessing hot data on NVM, *AC-BPFS* should perform similar to *BPFS*. If our design is right, eviction of cold data blocks by anti-cache manager in the background should not affect the performance of *AC-BPFS*. Cold data block access latency will be similar to that of *ext4* and this cost of accessing cold data on disk will be amortized in the presence of hot data accesses in the workloads. We run various micro-benchmarks and filebench [1] macro-benchmark to evaluate if these hypotheses are true.

4.1 Methodology and Setup

Making a meaningful performance comparison of *AC-BPFS* with both NVM file system such as *BPFS* and disk based file system such as *ext4*, presents challenges at different levels. We cannot make a comparison in isolation since our implementation is a hybrid approach that incorporates both NVM and disk. Since *ext4* filesystem buffers writes in operating system buffer cache, we issue *fsync* in our workloads so that the data is made durable on disk. This makes our comparison reasonable as issuing *sync* on *AC-BPFS* and *BPFS* flushes the CPU caches making the data durable on NVM.

For the purpose of the evaluation, we run our experiments on a real hardware with 8 CPU cores running Ubuntu linux operating system with 16 GB of main memory, 1 TB of hard disk drive. We simulate the behavior of NVM using DRAM due to unavailability of the hardware. Unless otherwise noted, both the original and our implementation of *BPFS* are mounted in 2GB of main memory. The anti-caching daemon is set to run at 10 ms by default with anti-caching threshold of 40 MB for micro-benchmarks while varying the anti-caching threshold for the macro-benchmark.

4.2 Micro-benchmarks

In this section we present an experimental evaluation of *AC-BPFS* on NVM and disk using a set of micro-benchmarks and offer comparisons with those of *BPFS* on NVM and *ext4* on disk.

4.2.1 Various Filesystem Operations

In order to ensure the correctness of various filesystem operations and to measure if there is any additional overhead due to anti-caching mechanisms implemented on top of *BPFS*, we benchmarked different file operations in *AC-BPFS* and compare the performance with that of *BPFS*. Table 1 shows a representative sample of those operations and latency for each of these operation for both *AC-BPFS* and *BPFS*. We benchmark *read*, *write* and *append* operations in a later subsection.

Analysis: The table 1 shows that for the file operations the added overhead is negligible, if any at

Operations	AC-BPFS latency(ms)	BPFS latency(ms)
chmod	5.26	5.19
create	6.49	6.45
link	6.21	6.24
mkdir	6.61	6.55
readdir	3.24	3.1
rename_dir	8.3	7.61
rename_file	8.6	7.82
rmdir	6.66	5.95
symlink	6.58	6.46
unlink_16M	10.03	10.42
unlink_hardlink	5.5	5.5

Table 1: **Micro-benchmark.** *This table shows a set of filesystem operations and latency for each of these operations in both AC-BPFS and BPFS*

all thus showing that the various anti-caching mechanisms implemented on top of *BPFS* do not add an additional overhead. The filesystem operations shown in table 1 do not include operations that access cold data and involve only meta data blocks like inode and directory entries except for unlink where data blocks on disk needs to be freed if any (Note that freeing of data blocks on dis is asynchronous and happens in the background). Hence all the accesses are to NVM, the performance of *AC-BPFS* and *BPFS* should be similar and the data reflects this.

4.2.2 Micro-benchmark: Append

We measured the cost of appending data chunks of various size to an empty file. The file system just contained an empty file at the boot of each run of the experiment. We called *fsync* after every write call to ensure that the data gets written to the disk in case of *ext4* and to NVM in case of *AC-BPFS* and *BPFS*. We used *clock_gettime* system call to measure the time for this benchmark. We repeated each append operation 100 times. Figure 3 shows the plot for average time taken per append for various append sizes.

Analysis: Figure 3 shows that both *AC-BPFS* and *BPFS* perform similar and are both faster than *ext4* in orders of magnitude. Append creates new data blocks and don't require cold data blocks to be fetched from disk. Since the writing of all the data for the *append* operation happened entirely in NVM, *AC-BPFS* and *BPFS* performance lines are virtually inseparable. This result justifies the anti-caching mechanism that we have employed and also

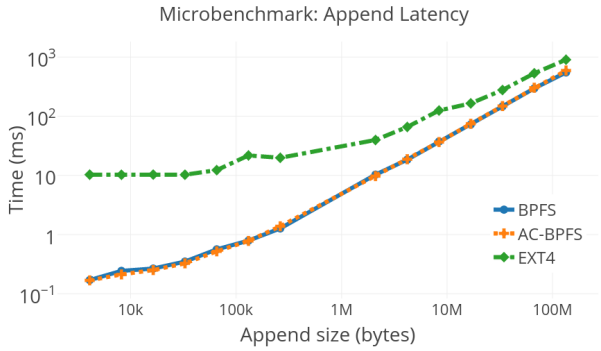


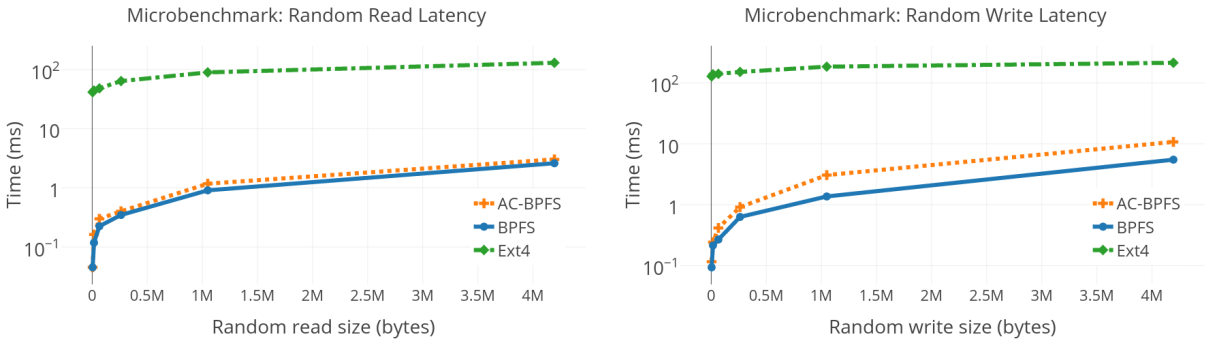
Figure 3: **Micro-benchmark: Append.** *The figure shows the append latency for various append sizes in AC-BPFS, BPFS and ext4. Note: x and y axes are in log scale.*

illustrates its low overhead. In our experimental setup, we set the anti-caching threshold of 40MB and hence appends of higher sizes blocks trigger eviction of blocks to disk. These evictions happen in the background and writes still go to NVM. Hence, this benchmark helps prove that the background eviction of cold blocks to disk doesn't affect the performance of *AC-BPFS*.

4.2.3 Micro-benchmark: Random Writes and Random Reads

We evaluated the performance of making random *write* and random *read* operations for various data sizes for *AC-BPFS*, *BPFS* and *ext4*. These random writes are in fact random overwrites and we dealt with appends in a separate benchmark. For *AC-BPFS*, we pre-generated files of various sizes and ensured that the total size of the data set exceeded the anti-caching threshold to force eviction of blocks to disk. This ensures distribution of random read and random write operations to data blocks in both persistent memory and disk. For random writes, we called *fsync* after every write call to force the data to disk so as to make even comparisons across the filesystems. Also to force random read from disk, we clear the operating system buffer cache by issuing *sync* [2] at the start of each run. This will force a seek to disk when accessing cold data in case of *AC-BPFS* while forcing random reads to disk all the time in case of *ext4*. We repeated each read and write operation 100 times and take the average latency for each operation.

Analysis: Figure 4(a) and figure 4(b) show the the plots for average time taken per random read and random write respectively for various data sizes.



(a) Micro-benchmark: Read *(b) Micro-benchmark: Write*

Figure 4: **Micro-benchmarks.** *Figures (a) and (b) shows the average random read latency and average random write latency respectively for various data sizes in AC-BPFS, BPFS and ext4. Note: y axis is in log scale.*

Since our requests are distributed across NVM and disk in case of *AC-BPFS*, random reads and random overwrites of data might require fetching of data blocks from disk for few requests while most of the requests go to NVM. We do not have the exact distribution of requests to disk and NVM as we chose blocks in random. We perform a controlled experiment in the next subsection. This explains the difference in latency between *AC-BPFS* and *BPFS* in figures 4(a) and 4(b). But, both *AC-BPFS* and *BPFS* are still faster than the *ext4* in orders of magnitude, as we hoped, thus reinforcing our initial intuition. Random writes are slower than random reads, as random overwrites of data in *BPFS* and *AC-BPFS* trigger shadow paging.

4.2.4 Micro-benchmark: Degree of hotness

This micro-benchmark demonstrates the effect of the anti-caching and plots the read latency of reading 400 KB data against the degree of hotness. As in the previous experiment, we clear the operating system buffer cache by issuing *sync* at the start of each run. For the benchmark, we read a 400 KB chunk of data split into ten requests of 40KB chunk per request, part of which can be hot/cold depending on the degree of hotness. To implement this benchmark, we create 10 files of 40 KB each and we fix our anti-caching threshold based on the hotness factor, so that at any given point only the percentage of files corresponding to the hotness factor can reside in NVM. Then a workload is created, which simulates the reading of certain number of files in the NVM vs the files in the disk, based on the degree of hotness. A 20% hotness factor on the X-axis for a

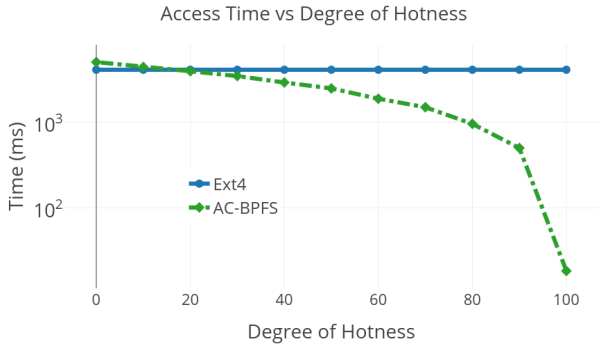


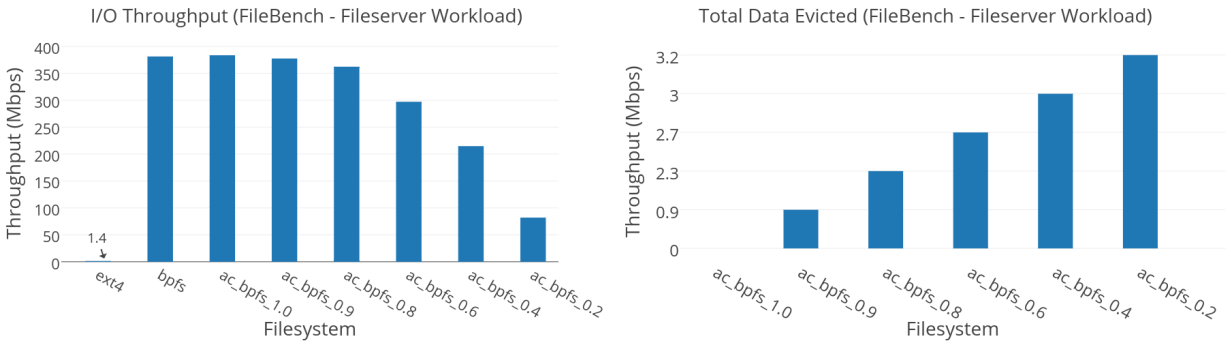
Figure 5: **Impact of Degree of Hotness on Read Latency.** *This figure shows the read latency for various degrees of hotness in AC-BPFS and ext4. Note: y axis is in log scale.*

400 KB chunk data size would mean that 320 KB of the *cold* data resides in disk, while 80 KB of *hot* data resides in NVM for *AC-BPFS*. The requests always go to disk for *ext4*.

Analysis: Figure 5 shows the read latency for reading 400 KB data for various degrees of hotness in *AC-BPFS* and *ext4*. As expected, the read latency for a 20% hot data would be more than the read latency for a 80% hot data. At a 0% hotness, the performance of *AC-BPFS* will flat-line with the *ext4* performance while at 100% hotness our performance is exactly what you would expect from *BPFS*. The more the degree of hotness, the more is the performance. This clearly proves the benefit of our anti-caching implementation for a tiered storage.

4.3 Macro-benchmark: Filebench

For this benchmark, we used Filebench [1] to test and compare the performance in terms of overall I/O throughput of the three files systems by gen-



(a) FileBench (FileServer) - I/O Throughput

(b) FileBench (FileServer) - Block Eviction Count

Figure 6: **Macro-benchmark: FileBench (FileServer).** *Figure (a) shows the I/O throughput of ext4, BPFS and AC-BPFS under varying anti-caching thresholds for the fileserver workload in Filebench. Figure (b) shows the total amount of data evicted from NVM to disk under various anti-caching thresholds for the FileBench fileserver workload in AC-BPFS*

erating a fileserver workload on a data set of size 1.25 GB. The workload is comprised of 33% read requests and 67% write requests. We modified the workload to issue an *fsync* after writes to make the data durable. For *AC-BPFS*, we ran the benchmark by varying the anti-caching thresholds from 20% of the workload size to 100% of the workload size. We did so in order to get insights on the effectiveness and overheads of the anti-caching mechanisms in addition to making comparison of the *AC-BPFS* with *BPFS* and *ext4* file systems.

Analysis: Figure 6(a) shows that when the caching threshold is 100% of the workload size (i.e. all the operations happen in the persistent memory), the performance of *AC-BPFS* is identical to that of *BPFS*, as we expected. As we decrease the anti-caching threshold, the performance suffers accordingly. On all times, the performance of the *AC-BPFS* is better than that of *ext4* on disk in orders of magnitude. Diving deeper, we measure the total data that was evicted to disk for various anti-caching thresholds. Figure 6(b) shows the total amount of data evicted from NVM to disk under various anti-caching thresholds in *AC-BPFS*. *ac_bpfs_1.0* denotes that the anti-caching threshold was set to 100% of workload size and hence no data was evicted to disk. At lower anti-caching threshold, more data is evicted to disk. For example at 20% eviction threshold, close to 3GB data is evicted to disk. This is greater than the workload size of 1.25GB as fetching of cold data from disk will evicts colder data from NVM. This indicates that atleast 1.75GB of data was fetched from disk. We didn't have control over the access pattern in the workload and the requests were randomly distributed across NVM and disk and 20% anti-caching threshold didn't correspond to 80% access to 20% hot data. With a 80-20 workload pattern, we believe the performance of AC-BPFS would have been better.

5 Related Work

Current research around file systems for NVM is focused on maximizing file system performance by exploiting higher I/O throughput guarantees of the byte-addressable persistent NVM [5, 7, 11, 13]. While a majority of the research in this area has tried to solve the problem of consistency, write ordering and atomicity associated with implementing file systems for NVM, there has been some related works in accelerating the performance of existing file systems using NVM [3,4]. While many file systems for NVM have been proposed as a replacement for traditional disk and flash-based file systems, our work proposes to enhance these file systems to function alongside the existing traditional disk and flash-based file systems. NOVA [13] takes a different approach than the byte-addressable persistent file system (BPFS) [5] as it implements a log structured file system that provides better concurrency by using separate logs for each inode and guarantees consistency by storing the journals in NVM. The overhead of garbage collection in LFS is also reduced in NOVA by exploiting the low random write latency of NVM when compared to the poor sequential write access latencies of SSDs and disks.

PMFS [7] is similar to other persistent memory file systems but provides transparent large page sup-

port for faster memory-mapped I/O and provides a way for applications to specify file sizes hints causing PMFS to use large pages for files data nodes. Aerie [11] provides a flexible file system architecture that aims to avoid the overhead of trapping into kernel while reading or writing to a file. It achieves this by splitting the functionality across different layers - a kernel layer that handles protection, allocation and addressing, a user library that directly accesses NVM for file reads, file writes and metadata reads, and a trusted service that coordinates updates to metadata.

Lv et. al. [9] propose a strategy named Hotness Aware Hit (HAT) for efficient buffer management in flash-based hybrid storage systems by dividing pages into three hotness categories: hot, warm and cold. In general, the hot, warm and cold pages are kept in main memory, flash and hard disk respectively according to the page access history and pages hotness. Our approach employs a similar strategy to determine the hotness of data and adapts it with the changes in the usage pattern by employing a multi-tier page reference history. However, our approach differs from this work because we do not use NVM merely for buffering of data; we use it as one of the storage devices in the multi-tier storage system with strategies to make placement decision during the runtime.

Ghandeharizadeh et. al. [8] propose a way to use knowledge about the frequencies of read and write requests to individual data items in order to determine the optimal cache configuration given a fixed budget. This paper considers both tiering and replication of data across the selected choices of storage media. Our approach is different in following ways- we only consider tiering approach and do not replicate data across the storage layers, and the decision of placement of data is done online based on the information such as available space in NVM, size of the data and last access time. A separate background process moves cold data from higher storage level (NVM) to lower level (SSD / disk).

6 Conclusion

Fast non-volatile memories (NVM) are byte addressable and offer latencies close to DRAM, but incur a higher predicted cost per byte. Combining the low latency of NVM and low cost of disk-based storage without regressing on the performance maximizes the best of the two worlds. In this paper, we present design, implementation and analysis of multi-tiered storage hierarchy consisting of NVRAM and Disk (or Flash) for File Systems, thereby providing a virtual impression of infinite NVM memory as well as the cheap upgrade in the disk performance with the amount of NVM available through the use of anti-caching mechanism.

7 Future Work

We identify several opportunities to extend this work in future. In this paper we did not get to do a thorough analysis on impacts and effects of hotness and coldness of data using multiple workloads and macro-benchmarks. We believe that doing so will reveal several potential areas to improve the system both functionally and architecturally. It is very important that we extensively evaluate and analyze crash consistency and reliability issues for this system in depth before extending the system. Lastly, since we simulated the NVM in DRAM, we did not get to evaluate the effects of persistent LRU cache on the performance of the system. Persistent LRU cache could have a significant effect on different aspects of the file system, such as boot time, that remains yet to be studied.

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