SMORE: A Cold Data Object Store for SMR Drives
(Extended Version)

Peter Macko, Xiongzi Ge, John Haskins, Jr.*, James Kelley, David Slik, Keith A. Smith, and Maxim G. Smith
NetApp, Inc., *Qualcomm
peter.macko@netapp.com, james.kelley@netapp.com, keith.smith@netapp.com

Abstract—Shingled magnetic recording (SMR) increases the capacity of magnetic hard drives, but it requires that each zone of a disk be written sequentially and erased in bulk. This makes SMR a good fit for workloads dominated by large data objects with limited churn. To explore this possibility, we have developed SMORE, an object storage system designed to reliably and efficiently store large, seldom-changing data objects on an array of host-managed or host-aware SMR disks.

SMORE uses a log-structured approach to accommodate the constraint that all writes to an SMR drive must be sequential within large shingled zones. It stripes data across zones on separate disks, using erasure coding to protect against drive failure. A separate garbage collection thread reclaim space by migrating live data out of the emptiest zones so that they can be trimmed and reused. An index stored on flash and backed up to the SMR drives maps object identifiers to on-disk locations. SMORE interleaves log records with object data within SMR zones to enable index recovery after a system crash (or failure of the flash device) without any additional logging mechanism.

SMORE achieves full disk bandwidth when ingesting data—with a variety of object sizes—and when reading large objects. Read performance declines for smaller object sizes where inter-object seek time dominates. With a worst-case pattern of random deletions, SMORE has a write amplification (not counting RAID parity) of less than 2.0 at 80% occupancy. By taking an index snapshot every two hours, SMORE recovers from crashes in less than a minute. More frequent snapshots allow faster recovery.

I. INTRODUCTION

Shingled magnetic recording (SMR) technology [1] provides the next major capacity increase for hard disk drives. Drive vendors have already shipped millions of SMR drives. Current SMR drives provide about 25% more capacity than conventional magnetic recording (CMR). The SMR advantage is expected to increase over time [2], making SMR a compelling technology for high-capacity storage.

In addition to increasing areal bit density, SMR drives introduce several challenges for storage software and applications. The most significant challenge is that SMR does not permit random writes. SMR drives are divided into large multi-megabyte zones that must be written sequentially. To overwrite any part of a zone, the entire zone must be logically erased and then rewritten from the beginning.

There are several ways of supporting SMR’s sequential write requirement. One approach is to rely on drive firmware to hide the complexities of SMR, similar to the way a flash translation layer does in an SSD. The disadvantages of this approach are that higher-level information from the file system cannot be used to optimize the use of the SMR drive and that it does not take advantage of using multiple drives. A different approach would be to write a new file system, or to adapt an existing one, to run on SMR drives. Although this would enable file system level optimizations for SMR, state-of-the art file systems are highly complex. It is feasible to quickly prototype a new file system as a proof of concept, but commercial-quality file systems take years to develop and mature to the point where they are stable, reliable, and performant [3], [4].

We have opted for a third approach. Rather than developing a general-purpose storage system, our goal is to build a specialized storage system targeting a workload that is well suited to SMR drives—storing cold object data. With the advent of flash memory drives, many traditional storage workloads are now serviced by flash. As a result, there is little benefit to designing, for example, a transaction-oriented system targeting workloads that are better served by flash. Instead, we focus on use cases that are appropriate to SMR drives or that are cost prohibitive to deploy on SSD.

Hard drives, and SMR drives in particular, offer excellent sequential throughput, support for dozens of seeks per second (in contrast with tape), and low-cost capacity as measured in dollars per TB. A large-scale cool storage tier for large, sequentially accessed media objects fits well with this profile. Typical media files are read and written sequentially and range in size from a few MB to many GB or TB, providing predominantly sequential access patterns. Media storage is important in many wide-spread use cases, including entertainment, medical imaging, surveillance, etc. Such media use cases already account for a significant fraction of new data, a trend that is expected to continue in the future [5].

Frequently accessed objects are cached or tiered in high-performance storage. But long-tailed access patterns inevitably lead to a regular stream of read requests that miss in the cache tier and display poor locality in the backing capacity tier. The ability to seek to requested objects in a handful of milliseconds supports the retrieval of objects in a more timely manner than could be achieved with tape.

The resulting storage system, our SMR Object REpository (SMORE), targets this workload. While we anticipate ample demand for affordable solutions targeting the bulk storage of media data, SMORE is also applicable to other use cases that can benefit from low-cost storage for large objects, including backups, virtual machine image libraries, and others.
SMORE is designed to provide the full bandwidth of the underlying SMR drives for streaming read and write access. Although it will accept small objects, the performance for this type of storage has not been optimized. The unpredictable nature of long-tail read accesses can be met by the modest seek profile of SMR drives. Finally, because we anticipate seldom changing data, the garbage collection overhead resulting from SMR write restrictions has only a modest impact on SMORE’s overall performance.

SMORE fills SMR zones sequentially, erasure coding data across zones on separate drives for reliability. As the client deletes objects and frees space, SMORE uses garbage collection to migrate live data from partially empty zones. The resulting empty zones can then be used to store new data. A working copy of object metadata is stored in an index on a cheap flash device. SMORE employs several techniques to optimize for the needs and limitations of SMR drives. The most important of these is interleaving a journal for crash recovery in the sequential stream of object writes.

SMORE can be used as a standalone storage system on a single machine, or it can be used as the local storage engine for nodes in a multinode storage system like HDFS [6]. The latter is advantageous, because replicating or erasure coding data across multiple nodes increases data availability and adds an additional layer of data protection in the face of node failures.

The contributions of this work are:
- A recovery-oriented object store design, in which the disks remain on-seek during most writes.
- Decreasing the metadata overhead by managing disks at the granularity of zone sets, which are groups of SMR zones from different spindles.
- A system for efficient storage of cold object data on SMR drives.
- A rigorous evaluation of the resulting design using recent SMR drives, measuring write amplification and recovery costs as well as basic system performance.

The rest of this paper is organized as follows. The following section reviews the basics of the shingled magnetic recording (SMR) technology. We then describe the design and implementation of SMORE in Sections III and IV and present experimental results in Section V. Section VI places SMORE in the broader research context, and Section VII concludes.

II. BACKGROUND

Shingled magnetic recording (SMR) allows more data to be packed onto each drive platter by partially overlapping the adjacent data tracks. Current SMR drives provide a 25% increase in areal density. Early researchers speculated that SMR technology will eventually reach twice the density of conventional magnetic recording (CMR) drives [1], [2], but it remains to be seen if that can be achieved.

This overlap introduces a significant trade-off: because the data tracks are partially overlapping, previously written data cannot be changed without also overwriting data on the subsequent track. Accordingly, groups of overlapping tracks, while randomly readable, are sequential-write-only. The drives partition the surface area of each platter into zones separated by guard bands (gaps between the tracks of data), allowing each zone to be written and erased separately. The typical capacity of a zone is measured in tens of megabytes.

SMR drives come in three varieties: drive-managed, host-managed, and host-aware [7]. Drive-managed SMR drives use a Shingle Translation Layer (STL) [8], which is analogous to a Flash Translation Layer (FTL) [9] in SSDs, to present an interface indistinguishable from that of a CMR drive, but their ease of use comes at the cost of performance [10].

SMORE is thus designed for host-managed and host-aware SMR drives, which provide better performance at the cost of higher software complexity. Host-managed drives expose all intricacies of SMR to the software and accept commands to perform zone selection, zone reads, zone writes, and zone deletes [11]. The drives automatically maintain for each zone a write pointer, where subsequent write operations will resume. There is no “rewind” command for backward movement within a zone, and the zone must be erased before overwriting it, similarly to erase blocks in flash. Erasing a zone resets that zone’s write pointer to the first block of the zone. Host-aware drives are a compromise between these two extremes, handling random writes by using an internal STL, but delivering maximum performance when treated as host-managed drives.
Disk 1, Zone 1
Disk 2, Zone 5
Disk 3, Zone 4

Fragment 1a
Fragment 1b
Fragment 1c
Fragment 2a
Fragment 2b
Fragment 2c

Layout Marker Blocks (Metadata)
Erasure-Coded Data

Fig. 2: Anatomy of a zone set. A zone set is an arbitrary set of zones from different SMR drives. SMORE chunks each object into equal-sized segments, erasure codes each segment across the multiple zones, and writes them to the zone set together with headers called the layout marker blocks. When a zone set becomes full, SMORE finishes it by writing a digest with the summary of the segments it holds.

III. ARCHITECTURE

This section describes the SMORE architecture. We start with a high-level overview of the key components and their interactions, and the following sections describe different parts of SMORE in detail and explain the execution flow for important operations.

At the high level, as illustrated in Figure 1, SMORE writes data and metadata in a log-structured format, erasure coded across multiple SMR drives, and uses a flash device to store the index that maps object IDs to their physical locations. We optionally front-end each drive with a small buffer (a few MB in size) in battery-backed RAM for coalescing small writes, which improves performance and space utilization. Any kind of NVRAM will suffice for buffering, but NVRAM technologies with limited write endurance (e.g., PCM) will require extra capacity for wear-leveling. For simplicity, we use the term NVRAM throughout this paper.

SMORE uses a log-structured design because it is well suited to the append-only nature of SMR drives. Like a log-structured file system [2], SMORE divides storage into large, contiguous regions that it fills sequentially. In SMORE, these regions are called zone sets. When SMORE needs more free space, it garbage collects partially empty zone sets and relocates the live data. Unlike log-structured file systems, however, SMORE is an object store and runs on an array of SMR drives. This leads to a different design.

A zone set is a group of zones, each from a different drive, that form an append-only container in which SMORE writes data. SMORE spreads data evenly across the zones in a zone set so that their write pointers advance together. At any time, SMORE has one or more zone sets open to receive new data.

Figure 2 shows the anatomy of a zone set. SMORE chunks incoming objects into segments and writes each segment to one of the open zone sets. SMORE divides each segment into equal-sized fragments and computes additional parity fragments so that the total number of data and parity fragments matches the number of drives in a zone set. SMORE writes each fragment to one of the zones in the zone set, starting with a header, called the layout marker block (LMB). Layout marker blocks, which are used for error detection and failure recovery, describe the segment they are attached to.

SMORE keeps track of all live segments (those that belong to live objects) in an index backed by the flash device. The index allows SMORE to efficiently look up the zone set and offset of each segment belonging to an object.

The segment is the basic unit of allocation and layout and is typically a few tens of megabytes. Segments provide several benefits. They reduce memory pressure by allowing SMORE to start writing an object to disk before the entire object is in memory. (We call this a streaming write.) Likewise, it lets SMORE handle objects that are too large to fit in a single zone set. Segments also ensure sequential on-disk layout by avoiding fine-grained interleaving when writing several objects concurrently. Finally, large segments minimize the amount of metadata (i.e., index entries) required for each object.

SMORE deletes an object by removing the object’s entries from the index. It also writes a tombstone to an open zone set as a persistent record of the deletion, which will be processed while recovering the index after a failure. The space occupied by deleted and overwritten objects is reclaimed in the background by the garbage collector.

Each zone in an opened zone set can be optionally front-ended with a small NVRAM-backed FIFO buffer, which allows the system to efficiently pack small objects even in the presence of large physical blocks (which could possibly reach 32KB or larger in the future [3]) and optimize write performance. Fragments and FIFO buffers are sized so that the system typically reads and writes 2 to 4 disk tracks at a time, amortizing the cost of each seek across a large data transfer.

SMORE follows a recovery-oriented design. By designing for fast and simple recovery, we can use SMORE’s recovery logic in place of more complex consistency mechanisms. There are a variety of failures that could damage the index. SMORE handles all of these scenarios with a single recovery mechanism—replaying updates based on the layout marker blocks intermingled with object data in zone sets. Using the same logic for multiple failure scenarios ensures better testing of critical recovery code. It also avoids the overhead and complexity of implementing different mechanisms to handle different faults.

SMORE periodically checkpoints the index, storing a copy in dedicated zone sets on the SMR drives. In the event of a failure, it reads the most recent checkpoint and updates it by scanning and processing all layout marker blocks written since the last checkpoint. As an optimization, SMORE writes a digest of all layout marker blocks of a zone set when closing it. During recovery, SMORE can read this digest in one I/O operation instead of scanning the entire zone set.

In summary, Figure 3 illustrates how data flows through the system on write: chunking it into segments, erasure coding, optional buffering in NVRAM-backed FIFO buffers, and finally writing to the zone sets. In the next section, we examine the
architecture in more detail and add relevant implementation details.

A. Versioning

When a client overwrites an existing object, SMORE temporarily needs to distinguish between the old and new versions of the object. SMORE must return the old version of the object in response to any GET request until the new version is complete. If SMORE fails before the new version of the object is completely written, it returns the old version (and not incomplete data from the new version) after the system restarts.

SMORE assigns a version number to each object by using a (64-bit) timestamp assigned at creation. These version numbers distinguish and serialize different versions of an object. We mark a version as complete by setting a special bit in the layout marker block of the last segment of the object (which is written while closing the object) and by setting the corresponding bit in its index entry. Old versions remain in the index until the newest version is fully durable, at which time they are deleted.

When retrieving an object, SMORE returns the complete version with the most recent time stamp. This ensures that while a new version is being written, any GETs of the object return the last complete version.

B. Zone Sets

When the system is initialized, SMORE statically creates all zone sets, assigning the same number of zones to each zone set. We call the number of zones in a zone set the zone-set width. For simplicity, we ensure that all zone sets have the same number of elements, each of the same size. But our architecture can handle zone sets with different widths, possibly varying over time. In principle we could also handle zones of different sizes, taking the length of the shortest zone as the length for all zones. Each zone set has a unique ID and we maintain a table, called the zone-set table, mapping zone set IDs to their constituent zones and respective disks.

The zones in a set are always filled in parallel with equal amounts of data striped across them, encoded by the data protection scheme specified at system initialization. Tombstones and zone-set digests are replicated across all zones in a zone set due to their small size. Moreover, the zones in a set are filled, closed, garbage collected, and trimmed as a group.

Because the write pointers are always advanced in synchrony, only one index entry is required to locate all the encoded fragments of a segment. This significantly reduces the size of the index. Each entry is simply a zone-set ID and an offset into the zones. Individual zones in a zone set can be relocated when adding, removing, or rebuilding disks, with only an update to the zone set table required.
A small amount of system-wide metadata is stored in a superblock. The superblock contains descriptors for each disk drive, the current zone-set table, and the location of index snapshots. Each superblock also contains a timestamp indicating the time it was written.

A small number of superblock zones are set aside on each disk to hold copies of the superblock. When writing the superblock, SMORE replicates it on to superblock zones on three different disks. (The number is configurable.) When a superblock zone is full and there exists a more recent superblock elsewhere, the zone is simply trimmed. During recovery, the superblock zones are examined to find the most recent superblock, which is used to bootstrap the rest of the recovery process.

C. Zone-Set States

A zone set advances through different states throughout its lifetime, as illustrated in Figure 4:

- **EMPTY**: Empty zone set (the initial state of all zone sets when a SMORE system is created).
- **AVAILABLE**: The zone set is still empty (it does not contain any data), but it is available to be opened and receive data.
- **OPEN**: The zone set can receive writes.
- **CLOSED**: The zone set is full and does not accept any more writes.
- **INDEXED**: A zone set that was CLOSED at the time of an index snapshot; it does not need to be examined during recovery.
- **INDEX**: (Not shown in Figure 4) A zone set that stores a snapshot of an index.

All zone sets start out as EMPTY and not available to be used by SMORE to store data. SMORE maintains a small pool of AVAILABLE zone sets (32 to 64 by default), which are also empty, but they can be opened and accept writes at any point.

To speed up recovery, we distinguish between two types of empty zone sets. Moving zone sets from the EMPTY state to the AVAILABLE state involves writing the superblock, so if a zone set is marked as EMPTY in the superblock, it is actually empty, and it does not need to be examined during recovery. A zone set marked as AVAILABLE in the superblock may contain data, so in the event of an unclean shutdown, it must be examined during recovery.

Only OPEN zone sets can receive writes, and when the zone set fills, it becomes CLOSED. Snapshooting the index transitions all CLOSED zone sets to the INDEXED state (and includes a superblock write to persist this change across a shutdown). This indicates that the zone sets do not need to be examined during recovery for the purposes of restoring the operational index.

CLOSED and INDEXED zone sets can be cleaned and trimmed without writing a superblock, so it is possible that zone sets with these states might actually be found to be empty during recovery. The recovery routine simply checks the write-pointers of all INDEXED zone sets, but it does not examine them further. We can alternatively wait for the zone set to be again garbage collected; cleaning an INDEXED zone set that is actually empty would then simply restore it to the EMPTY state.

D. Index

SMORE requires an index to translate an object ID into the locations on the SMR disks where data segments are stored. The index is simply a B+ tree, but it could be any other key-value store with the ability to search by prefix. The key is a tuple consisting of the object’s 256-bit ID, version number (the time of the object’s creation), segment ID, and a bit indicating whether this is the last segment of a complete object. The key maps to a value consisting of the zone-set identifier, the offset of the segment within that zone set (the offset is the same for all zones in the zone set), the length of the segment, and a timestamp of the entry. The timestamp indicates the time when the entry was written to disk and is useful for detecting stale index entries during recovery. The index is cached in RAM and backed up by files on the system’s flash, which are updated asynchronously.

The index must always be up to date and durable across system interruptions. Due to our requirement that SMORE must survive failure of the flash device, the SMR disks must at all times hold enough information to quickly restore the operational index. Index recovery is further constrained by our desire to ingest data at near bandwidth, precluding conventional journaling techniques, which introduce seeks between data and journal.

As described previously, SMORE writes a layout marker block with each fragment on disk. These records, along with tombstones, act as a journal of all updates to SMORE. Although it is possible reconstruct the index only by reading this information, SMORE provides two optimizations to make recovery more efficient. First, SMORE places a digest at the end of each zone set, summarizing the contents of all the layout marker blocks in that zone set. In most cases, this allows SMORE to use a single I/O to read all of the recovery information from a zone set, rather than seeking between the individual layout marker blocks. Second, SMORE periodically writes a checkpoint of the entire index to the SMR disks, limiting recovery work to reconstructing changes since the most recent checkpoint.

SMORE writes index checkpoints to specially marked zone sets (using the INDEX zone-set state). Because index segments do not mix with the data objects, SMORE can delete an old snapshot just by trimming the appropriate zone sets without involving the garbage collector.

Conventional B+ tree implementations require transactional support to ensure that changes affecting multiple blocks, such as merges and splits, are atomic. We have avoided this additional complexity. Index recovery using SMORE’s on-disk state is efficient enough that after any abnormal shutdown, SMORE ignores the possibly corrupt contents of flash and reconstructs the index from the most recent index checkpoint.

E. Garbage Collection (Cleaning)

When an object is deleted, its space is not immediately reclaimed, because those fragments became read-only once they
were written into the sequential zones. A zone set containing deleted data is said to be *dirty*. Eventually space is reclaimed from dirty zone sets by moving any live data into a new zone set, then trimming the old zones. This cleaning may be done on demand when more space is needed in the system or as a background task concurrent with normal client operation. Superblock and index snapshot zones are trimmed during normal operation and do not need cleaning.

SMORE uses a simple greedy strategy by always cleaning the zone set with the most dead space. Once a zone set is selected for cleaning, all of the live data is relocated to another zone set and only the tombstones that are newer than the most recent index snapshot are relocated. As the data and tombstones are relocated, the index is updated accordingly. After all valid items have been copied and indexed anew, the zones of the old zone set are trimmed and made available for writing new content. Note that a GET operation must acquire a shared lock on a zone set to prevent the object segment from being erased between the time of the index lookup and the disk reads.

If the node crashes during garbage collection, garbage collection can be begun anew after a reboot, starting from any zone set. Any incompletely cleaned zone set will eventually be selected again for cleaning. Content in the zone set that was cleaned previously will be found to be invalid at that time and discarded, while any still-valid content will be relocated.

**F. Client Operations**

This section summarizes the process of writing, reading, and deleting objects in SMORE.

1) **PUT**: Ingesting a client object occurs in two phases: first, the new object is stored and indexed; second, any previous versions are deleted. The object is split into smaller segments which are stored individually, and each segment is further split into a number of fragments, encoded with a data protection scheme, and stored together with its layout markers in the zone set. Dividing objects into segments allows SMORE to support streaming writes. An entry for each segment is added to the index and to the in-memory copy of the zone-set digest, which will be written when the zone set is closed.

Once the PUT operation completes, SMORE removes the index entries for any previous versions of the object. It is not necessary to write a tombstone record, because the segment of a more recent version of the object with the complete bit set implicitly acts as a tombstone for all previous versions.

After deleting the previous versions of the object, SMORE acknowledges the PUT operation as complete to the client. Concurrent PUTs of the same object do not interfere with each other or with concurrent GETs for previous versions of the object. Whichever PUT is assigned the latest version timestamp is the "most recent" version of the object. If the most recent PUT finishes before an older PUT, then there will be two versions of the object stored in SMORE. But the most recent will always be returned in GET requests, and the space occupied by the earlier version will eventually be reclaimed by garbage collection.

If there is a system crash after ingesting a segment, the recovery process restores the corresponding index entry by scanning zone sets that could have been written since the most recent index snapshot (i.e., zone sets in the AVAILABLE, OPEN, and CLOSED states) and reading the digests or walking from layout marker to layout marker to learn the recent ingests and deletes.

2) **GET**: When a client GET request arrives, SMORE first performs a look up of the object ID as a prefix in the index—which returns all versions stored in the index—and selects the most recent complete version. SMORE then reads the corresponding segments and assembles them into a complete object to return to the client. Any portions of older or newer versions (e.g., from a newly arriving PUT) do not contribute to the object returned to the client and are ignored. Newer versions are returned only to GETs that arrive after the PUT completes. As with PUTs, SMORE supports streaming reads.

3) **DELETE**: Client DELETE requests are assigned a timestamp immediately upon arrival. The timestamp serializes the DELETE with respect to other operations and prevents a DELETE from destructively interfering with a PUT arriving soon after and being processed concurrently. When a DELETE arrives, the object’s ID is looked up in the index. If it is not found, the request immediately completes with no action needed. If it is found, all portions of the object older than the timestamp of the DELETE are removed from the index. Then a tombstone is written into any currently open zone set and logged in the digest for that zone set.

The tombstone consists of a zone-set width number of copies of a layout marker announcing the deletion of the segment. If there is an interruption after the deletion, the tombstone will be processed during recovery, ensuring that the deletion operation will not be lost. The space occupied by the data will be reclaimed later by garbage collection.

**G. Recovery**

If a disk fails, all zone sets with a zone on the failed disk are degraded, relying on SMORE’s erasure coding to reconstruct missing data. To repair the damaged zone sets, SMORE walks the zone set table to find all of the zone sets that contain zones from the failed disk. For each such zone, SMORE replaces the failed zone with a free zone from a good drive. To ensure failure independence, SMORE selects a zone from a drive that does not already contain any zone in the affected zone set. SMORE then reads the zone digest from any surviving disk to identify its contents and reconstructs data into the new zone by using the erasure coding to rebuild object data and copying the replicated data structures. The replacement zones can be cannibalized from existing empty zone sets or taken from a replacement drive. Because index entries refer to zone sets by ID, the only metadata that needs to be updated is the zone set table.

Recall that SMORE optionally uses NVRAM to coalesce small writes into track-sized chunks to increase performance, especially in the presence of large disk block (e.g., 32 or 64KB). NVRAM is very reliable and unlikely to fail. If, however, it does
fail, or if the node’s motherboard fails—taking the NVRAM with it—then any data pending in the buffers is lost, and it must be recovered from other sources, such as peer nodes, if SMORE is used as a part of a distributed system. If NVRAM failure is nonetheless a concern, the FIFO buffers can be disabled, or a flush to disk can be performed before acknowledging the PUT to the client.

IV. IMPLEMENTATION

SMORE is implemented as a library in approximately 19,500 lines of C++ (excluding tests and utilities). We used libzbc [14] to interface with SMR drives. The SMORE library presents an object-based read/write API and can be linked into a higher-level storage service, such as OpenStack Swift, to provide a complete solution. SMORE supports multiple back ends for storing the data, including SMR drives, conventional disks treated like SMR drives, and a RAM disk storing just blocks containing the file-system metadata. The latter two are used for testing.

A. Index and Index Snapshots

SMORE maintains the index as a collection of files on a flash device using a standard file system, such as xfs [15] or ext4 [16]. We do not update the files synchronously or implement any recovery logic for the B+ tree; we instead depend on zone-set digests and layout marker blocks to recover the operational index from a consistent snapshot. The index snapshot is simply a consistent copy of these files, where each file is stored as an object in SMORE.

We maintain up to two snapshots: The most recent consistent snapshot, and a snapshot that may be in progress. As a part of the snapshotting process, we identify which INDEX zone sets do not belong to the most recent consistent snapshot and trim them.

We snapshot the index by briefly suspending changes (PUTs, DELETEs, and garbage collection) to make a complete and consistent copy stored on flash, and then allow changes to resume while we store the copy in dedicated zone sets in the background. For example, in a 50TB system, the pause would be on the order of a few hundred milliseconds to a few seconds, depending on the number of objects in the system. We reuse the same logic for storing the index snapshot as for storing the client data, with the exception of using dedicated zone sets. We index these fragments in an in-memory balanced tree, which we then serialize into the superblock and persist to superblock zones on the SMR drives.

1) Operational Index Recovery: The index recovery process begins by reading the most recent superblock from the SMR disks, which gives the location of the most recent complete snapshot of the index. SMORE then copies the snapshot to the flash device and examines each zone set that could have been written to since the last index snapshot. For closed zones, SMORE examines the zone-set digest, while zones that are still open must be traversed, moving from layout marker to layout marker. Examining these zone sets and updating the index as appropriate (e.g., removing entries for newly deleted objects) ensures that all changes to the index are recovered.

Layout marker blocks are timestamped—with each timestamp also saved in the corresponding index entry—and the timestamp is updated whenever the segment is relocated during garbage collection. This timestamp enables us to examine zone sets in any order, and determine whether we have already processed a more recent copy of a given segment.

When SMORE encounters a layout marker block for a tombstone, it adds it to a list of tombstones seen during recovery and removes all index entries for versions that are less than or equal to the version of the deleted object.

When SMORE encounters a layout marker block of an object segment, it:

1) Checks whether it has already seen a tombstone for this or a later version of the object, and if so, skips this segment, because it has already been deleted.
2) Checks whether the index already has a newer complete version of the object, and if so, skips this segment.
3) Checks whether the index has an entry with the same version but with a more recent timestamp, which indicates that the segment has been relocated, and if so skips this segment.
4) If all the checks pass, updates the index entry from this layout marker block.

When SMORE processes the last valid layout marker, it uses the zone’s write pointer to verify that the corresponding fragment was completely written. It computes the position where the fragment should end based on the size recorded in the layout marker. If this is past the current location of the write pointer, the fragment is incomplete. This relies on the assumption that a crash does not leave incompletely written data prior to the write pointer. If necessary, SMORE can use the checksum stored in the layout marker as an additional validation of the data.

B. Erasure Coding

The current SMORE implementation uses RAID 4 as its erasure code (for simplicity of implementation). Thus SMORE can recover from a single disk failure or from data corruption on a single drive. RAID 4 is implemented behind an abstract interface, allowing the use of different erasure codes in the future. For example, in a system with more SMR drives, a larger number of parity disks might be desirable.

C. Garbage Collection

Garbage collection (GC) runs as a background task, scanning the zone sets for dead space and relocating live objects to other, open zone sets to reclaim that dead space. SMORE runs GC more frequently when there are too few zone sets available to receive new client data.

SMORE maintains an accurate in-memory dead-space statistic for each non-empty zone set. The zone-set table stores the dead-space value at the time of the last index snapshot, because it is impractical to copy the zone-set table to the disk each time an object is deleted. SMORE recovers the accurate amount of dead space during recovery while processing tombstones.
V. Evaluation

We designed SMORE to support a cool storage tier for large media objects. Therefore our evaluation focuses on quantifying SMORE’s performance under different aspects of this workload. In particular we have tested SMORE for:

- Ingest performance
- Object retrieval performance
- Write amplification
- Recovery performance

In addition, we have performed more focused evaluations of specific design trade-offs in SMORE.

A. Test Platform

Our test platforms use six HGST Ultrastar Archive Ha10 drives. These are 10TB host-managed SMR drives with 256MB zones. According to our measurements, the average read performance is 118MB/s across all zones (with peak 150MB/s at the outer diameter) and the average write performance is 55MB/s (with 65MB/s at the outer diameter). The write bandwidth is lower than the read bandwidth because after the drive writes a track, it verifies the correctness of the previous track [17].

We restrict the capacity of the drives by using only every 60th zone. This limits the overall system capacity enough to make the duration of our benchmarks manageable while preserving the full seek profile of the drives. We configure our zone sets for 5+1 parity. The resulting total system capacity is 766GB. We verified that our results are representative by comparing them to the results of select test cases that we ran with the system’s full 50TB capacity.

The drives are connected to a server with 32 Intel Xeon 2.90GHz cores and 128GB RAM. SMORE uses direct I/O exclusively, bypassing any buffering in kernel, so that our results are not skewed by the large amount of main memory in our system.

B. Workload Generator

We generate our workloads with two different distributions of object sizes: (1) workloads in which all objects have the same size, ranging from 1MB to 1GB, and (2) workloads with object sizes that follow a truncated log-normal distribution. The peak of the distribution is around 128MB, with a majority of objects between 16MB and 512MB. We truncate the distribution to omit objects less than 1MB in size, since we assume that small objects will be stored further up in the storage hierarchy or coalesced into larger objects before being stored in SMORE. The largest object size in this distribution is 10GB. This distribution is modeled after the file sizes in the cold storage system of the European Center for Medium-Range Weather Forecasts [13], which is representative of the types of workloads we expect SMORE to be used for. In all tests, PUT and GET operations read and write entire objects.

The workload generator takes a target utilization as a parameter and it creates and deletes objects to keep the percentage of live data in the system around that value. Specifically, when a new object is created, the generator deletes older objects at random to free space for the object. Random object deletion ensures that we induce worst-case garbage collection performance.

C. Ingest Performance

When bringing a new storage system into service, an early step is often to migrate files onto it from other (older) systems. Because data ingest typically involves large volumes of data, high performance is important during this step. And because early impressions are lasting impressions, high performance is also important in ensuring customer satisfaction.

To measure ingest performance, we look at workloads consisting of 100% PUT operations until the system fills up. We also vary the object sizes from 1MB to 1GB and the number of threads from 3 to 24. SMORE ingests data at approximately 280MB/s regardless of object sizes and the number of threads, which is almost exactly 100% of the maximum write bandwidth allowed by our SMR drives [1]. As long as any input data is available, SMORE streams it sequentially onto the SMR drives, ensuring the maximum possible performance. The performance does not depend on object size because per-object overheads are negligible. It does not depend on the number of threads because with only six drives, the system quickly becomes disk limited. In larger configurations, it may take more threads to saturate the system.

D. Object Retrieval Performance

SMORE is intended for cool data, not for completely cold data. Frequently accessed data is served from caches or tiers above SMORE. But SMORE still needs to serve requests for less frequently accessed data that is not stored in the faster tiers of the storage hierarchy.

1 In theory, the maximum write bandwidth is 5 × 55MB/s = 275MB/s, but the initial fill of the system stops short a few zones before reaching the inner diameter of the drives, resulting in slightly higher overall performance.
Because read requests are filtered by higher tiers, the workload to SMORE appears random. So this section evaluates SMORE’s performance in handling random read requests.

To evaluate read performance, we fill our test system to 80% of its capacity with (1) objects of the same size, ranging from 1MB to 1GB, to understand the effect of average read size on performance, and (2) a realistic mix of object sizes to get an overall performance number. We read objects at random, and in each case we read the selected object in its entirety. We use six threads and report the aggregate read bandwidth from SMORE.

Figure 5 shows the aggregate read bandwidth as a function of object size. The best possible read performance allowed by our disks is $5 \times 118 = 590$MB/s (the dashed line in the figure). SMORE achieves near-optimal read performance for large objects, but the read performance of small objects is dominated by seeks.

The read performance remains constant as the system ages. For example, we filled the system with a mixture of object sizes and aged it by deleting and creating new objects until we wrote more bytes than 500% of capacity of the system, which is a higher churn than we expect for cold data. We then measured the read performance again by reading random objects in their entirety. The resulting aggregate bandwidth was within the margin of error of read performance that we measured on an unaged system.

SMORE achieves good read performance because it attempts to keep segments from a single object close together. By default, it schedules writes to zone sets so that a single writer can write 12 segments of data (240MB before erasure coding, which is 48MB per drive) from a single object before switching to a different writer. The garbage collector then does a best effort to keep the fragments together. The lowered concurrency for writes is practically unnoticeable in large object workloads, while the read gains are significant.

To quantify this gain in read performance, we repeated our benchmarks with this feature disabled, so that segments from different objects are more interleaved. The read performance caps at 390MB/s, compared to 570MB/s from our original benchmarks. The amount of data that a thread can write at a time is configurable, so that the administrator can fine-tune the balance between achieving low latency for PUTs of small objects and achieving high bandwidth for reading large objects.

E. Write Amplification

Object ingest and retrieval are the foreground operations that SMORE performs on behalf of clients. But SMORE’s log-structured layout imposes additional overhead in the form of garbage collection. We measure this overhead as write amplification, which measures the total amount of data that SMORE writes relative to the amount of data ingested from clients. Write amplification quantifies the amount of extra work that the garbage collection imposes on the system.

However, we do not expect the client applications to experience much of this overhead in practice. We expect a cold storage system like SMORE to experience substantial idle time during which SMORE can perform GC without a negative impact on client performance. Perhaps a bigger concern is keeping the amount of I/O within the workload rate limit, which tends to be lower for SMR drives. For example, the workload rate limit for a different SMR drive from Seagate is 180 TB/year [20]. (The data sheet for our HGST drives does not specify the workload rate limit.)

We measure the write amplification by repeating our benchmark on a system that already contains data. We delete objects at random as fast as new objects arrive, which provides the worst-case measurement of the GC overhead. We expect the

Fig. 6: Write amplification as a function of object size and system utilization. The theoretically best write amplification is 1.2 (the dashed line), given our 5+1 zone set configuration. SMORE achieves good write amplification, especially for 70% utilization, and 80% utilization for larger object sizes.

Fig. 7: Time to create a snapshot vs. object sizes for a system with 80% occupancy.
delays to be at least weakly correlated in practice. We run three sets of benchmarks, each measuring the write amplification while maintaining different proportions of live data in the system: 70%, 80%, and 90%.

Figure 4 summarizes our results. Note that the best write amplification we can achieve is 1.2, due to our 5+1 zone set parity configuration (represented by the dashed line in the figure). SMORE achieves good write amplification, especially for 70% utilization, and even for 80% utilization with large objects.

Write amplification is particularly high for large utilization levels and small object sizes, because objects are deleted at random. As objects get smaller, there is less variance in the amount of dead data per zone set. As a result, the greedy garbage collector has to copy more live data when cleaning zone sets. For example, deleting a single 1GB object typically results in a lot of dead data in a few zone sets. Deleting an equivalent amount of data in randomly selected 1MB objects results in a smattering of dead data in a large number of zone sets.

F. Recovery Performance

System crashes should be rare events. But experience has taught us that failures do occur in the real world, and that it is important for a system to provide timely recovery. In SMORE, recovery consists of two phases: reading the most recent index snapshot, and then updating it from the zone digests and layout marker blocks in the recently updated zone sets. We can tune SMORE for faster recovery by taking more frequent index snapshots.

1) Creating Snapshots: Considering that SMORE is tuned for large objects, the overhead of snapshots is not significant. Figure 7 shows the time it takes to create an index snapshot for an 80% full system for various object sizes. The plot shows both the time it takes to create a snapshot just on the flash and the additional time it takes to copy it to the SMR drives. The time to create a snapshot depends primarily on the number of segments stored in the object store but not on the time since the last snapshot, because our snapshots are not incremental.

For all workloads except for the pure 1MB objects, it takes less than 0.15 seconds to create a snapshot on our test system. After extrapolating out the result to a 50TB system with mixed object sizes, we see that creating a snapshot would take approximately 1.5 to 1.6 seconds.

Copying to the SMR involves simply a single seek and sequential write of the snapshot, because snapshots are stored in dedicated zone sets, and in the vast majority of cases, the index fits inside a single zone set. In the case of the mixed workload, the index is less than 1 MB in size. This would fit into a single zone set even when extrapolated to a 50 TB system. On the other hand, because copying to SMR is asynchronous, the actual time to perform the snapshot might be longer, depending on the foreground workload.

In our current implementation, snapshotting to flash is synchronous, even though copying to the SMR drives is asynchronous. It is, however, possible to implement the entire process asynchronously to hide all of the latency from clients. It is also possible to lessen the overhead even further by copying only every n-th snapshot to the SMR drives.

2) Recovery: To evaluate the trade-off between faster recovery and taking more frequent snapshots, we measure recovery time as a function of the time since the last snapshot, which increases with the number of zone sets that need to be replayed.

Figure 8(a) shows the time it takes to recover SMORE for a workload with a mix of object sizes as a function of time from the most recent snapshot. In this benchmark, we took a snapshot after filling up the system to 80% of its capacity and then continued with a 100% PUT workload, varying the amount of time we allowed the system to run until we crashed it. (The crashing mechanism itself was approximate and non-deterministic as to when exactly it caused a crash. Therefore there is uneven spacing of data points in Figures 8(a) and (b).) After each crash, we measured the time required for recovery as well as the number of zone sets the recovery process examined.

This models the most common case, in which SMORE recovers starting from an index snapshot stored on the flash device, and only if that fails (which is very rare) it uses the index snapshot backup stored on the SMR drives. When we reran our recovery benchmark with an empty flash device, it took 0.28 seconds to copy the index snapshot from the SMR drives to the flash.

With zero zone sets to replay, we see the best-case time, where the most recent index snapshot is fully up to date. At the other extreme, when we recover every zone set (the last two data points in the plot), we see the worst-case performance. Seven seconds is thus the longest possible duration of recovery in our test system. When we need to recover every zone set, we do not need to start from an index snapshot.

As illustrated by Figure 8(b), the trend is linear with the number of examined zone sets ($R^2 > 0.999$). Since our tests use only 1 in 60 zones, we can extrapolate this to a 50TB system that uses the full capacity of the SMR drives and see that it would take only 7 minutes to recover the index in the worst case. Our recovery performance is limited by the time required to read the digest from each zone set. Thus it should increase on larger drives with more SMR zones, but it should not increase on systems that use more than six drives.

In our current implementation, SMORE recovers the index by reading all digests from the same disk, but since digests are replicated instead of erasure coded, a more optimal way would be to spread the reads across all drives. Given the six drives in our test platform, this more optimal implementation would recover about six times faster (i.e., in roughly 70 seconds).

The overhead of creating snapshots and the time it takes to recover can be balanced to meet a specific recovery time objective. For example, if the system needs to recover from a crash within 5 seconds, we need to take a snapshot approximately every 2 hours. If it takes less than 0.15 seconds to take a snapshot, then the overhead of snapshotting is only $2.1 \times 10^{-3}\%$. Even when extrapolated to a 50TB system with
VI. RELATED WORK

SMORE builds on a long history of write-optimized storage systems, dating back to the Sprite Log-Structured File System (LFS) [12]. Like LFS, SMORE writes all data sequentially to large disk regions (segments in LFS, zone sets in SMORE). Where LFS stages an entire segment in memory before committing it to disk, SMORE writes zone sets incrementally, so it can ensure that writes are stable before acknowledging them. This leads to SMORE’s use of layout marker blocks to enable recovery. In contrast to LFS, SMORE is an object store rather than a file system and maintains a working copy of its metadata in flash.

Sawmill [21] extended LFS to work on a RAID array, leveraging the write coalescing behavior of LFS to avoid small update penalties in RAID. Several LFS-inspired file systems, starting with WAFL [22] and followed by ZFS [4] and btrfs [3], have integrated RAID functionality within the file system, achieving the same benefits of avoiding or minimizing RAID update overheads. These systems also relaxed the sequential write requirements of LFS, trading smaller writes for lower (or no) cleaning costs. SMORE also integrates RAID functionality, but maintains strict adherence to LFS-style writes due to the requirements of SMR. Hence SMORE’s use of garbage collection to vacate zone sets before reusing them.

A. SMR File Systems

Several earlier projects have explored file system designs to accommodate the append-only nature of SMR writes. These designs share several attributes with SMORE. They all use log-structured techniques to ensure the sequential write patterns required by SMR drives, and they place the primary copy of their metadata on a random write device, such as an unshingled section of the SMR drive [23], [24], or on an SSD if it is available [25].

Like SMORE, HiSMRfs [25] spans multiple SMR drives by striping file data across them. Unlike SMORE, HiSMRfs is a general-purpose file system, leading to different design choices in other areas. In particular, HiSMRfs keeps a permanent copy of its metadata along with hot file data on mirrored SSDs. It uses a conventional file system journal (also stored on SSD) to provide fault tolerance. In contrast, the SMORE design targets cold data and aims to minimize the cost of storing this class of data. In particular, SMORE limits the amount of SSD storage it uses, storing only a single copy of the metadata index on flash and using log records embedded in zone sets to provide failure recovery. Our work also extends the HiSMRfs results by evaluating SMR performance with garbage collection and quantifying recovery overheads.

Huawei’s Key-Value Store (KVS) [26] is a single-disk system with some similarities to SMORE, such as a recovery-oriented design and snapshotting of an in-memory index to the SMR drive. Its key-value interface is similar to SMORE’s object interface. (That is, it stores very large values.) Cross-drive replication and erasure coding are handled at a high level in the Huawei Object Storage Stack. SMORE is instead designed as a multidisk system from the ground up, which decreases the index size and simplifies data management and recovery.

The SMR-aware Append-only File System (SAFS) [27] is a proposed design for a single-disk system. It is optimized for append-only workloads, such as long-term collection of sensor or surveillance data. It writes new data from all files into a single zone, but anticipating the interleaving of data from different files, SAFS later rewrites newly ingested data, separating the files into different zones. This optimizes for sequential reads at the cost of rewriting all data. In contrast, SMORE uses segments to write multiple megabytes of data to an object without interleaving.
Kadekodi et al. [28] demonstrated the benefit of building a file system on a hypothetical Caveat-Scriptor SMR disk that allows random writes instead of purely sequential writes, allowing workloads to run significantly longer before needing to clean. Moreover, the latency and throughput were better.

Finally, SMRDB [29] is a key-value store for database-like workloads, based on a Log-Structured Merge (LSM) Tree optimized for an SMR disk. It stores data in two levels, L0 and L1, each consisting of logs sorted by keys.

B. Shingle Translation Layers (STLs)

Another method to incorporate SMR drives into a storage system is by using a shingle translation layer, similar to drive-managed SMR drives. For example, Set-Aware Disk Cache STL (SADC) [8], also called Set-Associative STL [10], writes incoming data to a persistent cache in a set-associative manner and later moves the data to the “native” zones by using read-modify-write. Similarly, Fully Associative STL [10] first writes data to an empty band, merges it later with the original band, and writes the data to a third band, freeing the first two bands in the process.

SMR disks that allow random writes to shingled zones enable STLs that take advantage of circular buffers [8], [30], [31] or managing data at the level of small, wedge-shaped regions [32]. Using drives with only a few tracks per zone enables efficient static address mapping schemes [33].

C. Other Related Work

Aghayev and Desnoyers [10] and Wu et al. [34] provide benchmark-based analysis of the behavior of commercial drive-managed and host-aware SMR drives, respectively.

Categorizing data based on hotness can significantly decrease write amplification on SMR drives [31], [35], [36], and has also been found helpful in the Flash-Friendly File System (FFFS) [37]. In addition to developing custom file systems and object stores for SMR drives, there is an ongoing effort to adapt existing file systems, such as ext4 [38], nilfs [39], and xfs [40] to SMR drives.

The technique of varying zone-set membership to balance rebuild load across drives adapts parity declustering [41] to SMR drives by aligning parity stripes to SMR zones. SMORE’s zone-set table introduced a layer of indirection not available in parity declustering, allowing greater flexibility in constructing zone sets (parity stripes). This lets SMORE rebuild into vacant zones on existing disks, rather than requiring a spare drive as in typical RAID systems.

Finally, there is a rich history of archival storage systems built using conventional hard drives. Some of this work describes complete systems [42], [43], [44]. Other researchers have focused on specific problems, such as data reduction [45], [46], power management [47], [48], or long-term data preservation [49], [50]. This research predates the introduction of SMR technology and does not address the unique requirements of SMR disks.

VII. Conclusion

In this work, we presented SMORE, an object storage system designed to reliably and efficiently store large, seldom-changing data objects on an array of host-managed or host-aware SMR disks. Using a log-structured approach to write data into the large, append-only shingled zones, we were able to achieve full disk bandwidth when ingesting data—for a variety of object sizes—with only a moderate amount of system optimization. Moreover, SMORE achieves low write amplification during worst-case churn when the system is filled to 80% of its capacity. Finally, the recovery-oriented design of SMORE, specifically the interleaving of log records with object data, allows a simple and efficient recovery process in the event of a failure without any additional logging mechanism.

ACKNOWLEDGMENTS

We would like to thank the anonymous FAST and MSST reviewers for their helpful comments on previous drafts of this paper. We also thank Al Andux, Tim Emami, Jeffrey Heller, and all of NetApp’s Advanced Technology Group (ATG) for their advice, support, and suggestions throughout this project. A shorter version of this paper will be published at the 33rd International Conference on Massive Storage Systems and Technology (MSST 2017) in May, 2017.

REFERENCES

[1] R. Wood, M. Williams, A. Kavic, and J. Miles, “The feasibility of magnetic recording at 10 terabits per square inch on conventional media,” IEEE Transactions on Magnetics, vol. 45, no. 2, pp. 917–923, Feb. 2009.
[2] G. A. Gibson and G. Ganger, “Principles of operation for shingled disk devices,” CMU Parallel Data Laboratory, Tech. Rep. CMU-PDL-11-107, Apr. 2011.
[3] O. Rodeh, J. Bacik, and C. Mason, “BTRFS, the Linux B-tree filesystem,” ACM Transactions on Storage, vol. 9, no. 3, pp. 9:1–9:32, Aug. 2013.
[4] M. K. McKusick, G. V. Neville-Neil, and R. N. M. Watson, The Design and Implementation of the FreeBSD Operating System, 2nd ed. Addison Wesley, 2015, ch. 10.
[5] J. Gantz and D. Reinsel, “The digital universe in 2020: Big data, bigger digital shadows, and biggest growth in the far east,” IDC iView Report, http://www.emc.com/collateral/analyst-reports/idc-the-digital-universe-in-2020.pdf, Dec. 2012.
[6] K. Shivachok, H. Kuang, S. Radia, and R. Chansler, “The Hadoop distributed file system,” in 2010 IEEE 26th Symposium on Mass Storage Systems and Technologies, ser. MSST ’10. IEEE Computer Society, May 2010, pp. 1–10.
[7] T. Feldman and G. A. Gibson, “Shingled magnetic recording: Areal density increase requires new data management,” ;login:, vol. 38, no. 3, pp. 22–30, Jun. 2013.
[8] Y. Cassuto, M. A. A. Sanvido, C. Guyot, D. R. Hall, and Z. Bandic, “Indirection systems for shingled-recording disk drives,” in 2010 IEEE 26th Symposium on Mass Storage Systems and Technologies, ser. MSST ’10. IEEE Computer Society, May 2010, pp. 1–14.
[9] D. Ma, J. Feng, and G. Li, “A survey of address translation technologies for flash memories,” ACM Computing Surveys, vol. 46, no. 3, pp. 36:1–36:39, Jan. 2014.
[10] A. Aghayev and P. Desnoyers, “Skylight – a window on shingled disk operation,” in Proceedings of the 13th USENIX Conference on File and Storage Technologies, ser. FAST’15, Feb. 2015, pp. 135–149.
[11] INCITS T10 Technical Committee, “Zoned block commands (ZBC), Draft Standard T10/BSR INCITS 536,” http://www.t10.org/drafts.htm#ZBC_Family, Dec. 2015.
[12] M. Rosenblum and J. Ousterhout, “The design and implementation of a log-structured file system,” ACM Transactions on Computer Systems, vol. 10, no. 1, pp. 26–52, Feb. 1992.
[13] J. Edge, “Handling 32kb-block drives,” https://lwn.net/Articles/636978/, Mar. 2015.
