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Performance testing of Virtual Data Optimizer storage layer

MASTER'S THESIS

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Brno, Spring 2020

Declaration

Hereby I declare that this paper is my original authorial work, which I have worked out on my own. All sources, references, and literature used or excerpted during elaboration of this work are properly cited and listed in complete reference to the due source.

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Acknowledgements

I would like to thank my self for tremendous help and guidance during writing of this thesis. I would also like to thank Red Hat for collaboration and provision of necessary testing equipment.

Abstract

Abstrakt sa pise nakoniec

Keywords

file system, performance, aging, benchmarking, fragmentation, storage, trim, fs-drift, XFS, VDO

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1 Introduction

Storage requirements of modern IT industry grows exponentially, but even while cost of storage devices is decreasing, new solutions for optimal storage utilisation need to be implemented. In Linux there is a large family of storage administration tools called *Logical Volume Manager* (i.e. LVM) that provides users with means of managing storage.

By using LVM and other tools available in Linux Kernel, users are able to create complex, layered abstraction which helps them utilise physical storage in the way that suits their needs. This complex structure of physical device management is generally called storage stack. In storage stack, different layers represent needed form of abstraction for working with the devices. These layers can have multitude of functions such as software RAID, encryption, caching, back up, thin provisioning or space saving.

Space saving is delivered by installing the *Virtual Data Optimizer* (i.e. VDO) layer. This layer is able to deduplicate and compress user data on the fly, making it possible to create logical volumes larger than available physical space. This storage is therefore *thinly provisioned*, however is different from the thin pool technology, because (given the user data are compressible enough), it can actually hold more data.

There are two main techniques used by VDO to save space. The first one is *deduplication*, which is a way to identify and eliminate multiple copies of the same data, preventing them to occupy physical space. The second technique is *compression*, that shrinks already deduplicated data furthering the space saving ratio.

Space saving presents users with serious advantage, since the cost of installing and maintaining a layer like this is much lower than the cost of purchasing more physical storage. However, on the fly manipulations of large quantities of data may seem costly in terms of usage of other resources like memory or CPU.

An important part of VDO technology is to make sure the costs of running VDO does not out-cost other approaches like purchasing more resources. VDO includes multitude of internal structures and logic, tunable by users, to ensure its advantages.

Because of aforementioned reasons, performance testing is an important part of developing and administering VDO. Users and de-

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development teams need to ensure the final product meets industrial quality standards.

However, performance testing of such a complex technology requires extended knowledge of its internal structures and advanced expertise in benchmarking.

This thesis aims to lay a foundational work for performance testing of VDO, describing its workings, performance related structures and issues and describing ways of benchmarking VDO.

Chapter 2 is an introduction of VDO technology. Space saving mechanisms will be described as well as VDO terminology, device organisation, system requirements, administration and relation to other layers in storage stack.

Chapter 3 presents used benchmarks, FIO and fs-drift, and their usage in testing VDO technology. New features for testing VDO were implemented for fs-drift and will be described in this chapter.

Chapter 5 is focused on performance testing of VDO. The testing is aimed on different VDO components as well as more complex deployment cases. Either way, results of the testing are presented giving recommendation for VDO usage and test its performance.

In Chapter 6, high-level insight on performance testing of VDO is given with recommendation for further work.

2 Virtual Data Optimiser

2.1 Introduction

Virtual Data Optimizer (VDO) is a block layer virtualisation service in Linux storage stack. VDO enables user to operate with greater logical volume than it's physically available. This is achieved by using compression and deduplication.

Deduplication is a technique that, on a block level, disallows multiple copies of the same data to be written to physical device. In VDO, duplicate blocks are detected but only one copy is physically stored. Subsequent copies then only reference the address of the stored block. Blocks that are deduplicated therefore share one physical address.

Compression is a technique that reduces usage of physical device by identifying and eliminating redundancy in data. In VDO, lossless compression, based on a parallelized packaging algorithm is used to handle many compression operations at once. Compressed blocks are stored in a way that allows the most logical blocks to be stored in one physical block.

The actual VDO technology consists of two kernel modules. First module, called *kvdo*, loads into the Linux Device Mapper layer to provide a deduplicated, compressed, and thinly provisioned block storage volume. Second module called *uds* communicates with the Universal Deduplication Service (UDS) index on the volume and analyzes data for duplicates.

2.1.1 Deduplication

Deduplication limits writing multiple copies of the same data by detecting duplicate blocks. Blocks that are duplicate of a block that VDO has already seen are stored as references for that block, which saves space on the underlying device.

Deduplication in VDO relies on growing UDS index. Hash from any incoming block, requested to be written, is searched for in the UDS index. In case the index contains an entry with the same hash, *kvdo* reads the block from physical device and compare it to the requested block byte-by-byte to ensure they are actually identical.

In case they are, block map is updated in a way that the logical block points to the block on underlying device that has been already written. If the index doesn't contain the computed hash or the block-by-block comparison identifies a difference in the blocks, *kvdo* updates the block map and stores the requested block.

Either way, the blocks hash is written to the beginning of the index. This index is held in memory to present quick deduplication advice to the VDO volume.

Logical blocks that are copies and therefore share one physical block are called *shared* blocks.

2.1.2 Compression

Another part of VDO optimisation techniques is compression. By compressing already deduplicated blocks, VDO provides one more step to increase utilisation of underlying device. Compression is also important for saving space in case the incoming data are not well deduplicable.

In VDO, lossless compression, based on a parallelized packaging algorithm is used to handle many compression operations at once. Compressed blocks are stored in a way that allows the most logical blocks to be stored in one physical block.

2.1.3 Zero-block elimination

Zero-blocks are blocks that are composed entirely of zeroes. These blocks are handled differently than normal data blocks.

If the VDO layer detects a zero-block, it will treat it as a discard, thus VDO will not send a write request to the underlying layer. Instead, it will mark the block as free on a physical device (if it was not a shared block) and updates its block map.

Because of this, if user wants to manually free some space, they can store a file filled with binary zeroes and delete.

2.2 Constrains and requirements

VDO layer is in fact another block device that can aggregate physical storage, partitions etc. On creation of VDO volume, management tool

also creates volume for UDS index as well as volume to store actual data.

2.2.1 Physical Size

The VDO volume for physically storing data is divided into continuous regions of physical space of constant size. These regions are called *slabs* and may be of size of any power of 2 multiple of 128 MB up to 32 GB. After creating VDO volume, the slab size cannot be changed. However, a single VDO volume can contain only up to 8096 slabs, so the configured size of slab at VDO volume creation determines its maximum allowed physical size. Since the maximum slab size is 32 GB and maximum number of slabs is 8096, the maximum volume of physical storage usable by VDO is 256 TB. Important thing to notice is that at least one slab will be reserved for VDO metadata and wouldn't be used for storing data. Slab size does not affect VDO performance. As mentioned, at least one *slab* is reserved for VDO metadata and UDS on-disk index.

VDO module keeps two kinds of metadata which differ in the scale of required space.

1. type scales with physical size and uses about 1 MB per every 4 GB of managed physical storage and also additional 1 MB per *slab*.
2. type scales with logical size and uses approximately 1.25 MB for every 1 GB of logical storage, rounded up to the nearest slab.

When trying to examine physical size, the term Physical size stands for overall size of underlying device. Available physical size stands for the portion of physical size, that can actually hold user data. The part that does not hold user data is used for storing VDO metadata.

2.2.2 Logical Size

The concept of VDO offers a way for users to overprovision the underlying volume. At the time of creation of VDO volume, user can specify its logical size, which can be much larger than the size of physical underlying storage. The user should be able to predict the compressibility of future incoming data and set the logical volume

accordingly. At maximum, VDO supports up to 254 times the size of physical volume which amounts to maximum logical size of 4 PB.

2.2.3 Memory

The VDO module itself requires 370 MB and additional 268 MB per every 1 TB of used physical storage. Users are therefore expected to compute the needed memory volume and act accordingly.

Another module that consumes memory is the UDS index. However, several mechanisms are in place to ensure the memory consumption does not offset the advantages of VDO usage.

There are two parts to UDS memory usage. First is a compact representation in RAM that contains at most one entry per unique block, that is used for deduplication advice. Second is stored on-disk that keeps track of all blocks presented to UDS. The part stored in RAM tracks only most recent blocks and is called *deduplication window*. Despite it being only index of recent data, most datasets with large levels of possible deduplication also show a high degree of temporal locality, according to developers. This allows for having only a fraction of the UDS index in memory, while still maintaining high levels of deduplication. Were not for this fact, memory requirements for UDS index would be so high that it would out-cost the advantages of VDO usage completely.

For better memory usage, UDS's Sparse Indexing feature was introduced to the uds module. This feature further exploits the temporal locality quality by holding only the most relevant index entries in the memory. Using this feature (which is recommended default for VDO) allows for maintaining up to ten times larger deduplication window while maintaining the same memory requirements.

2.2.4 CPU

2.3 Internal structures

Working VDO instance contains structures that handle the incoming events.

2.3.1 Slabs

2.3.2 Recovery journal

Recovery journal provides track of all block changes that has yet to be fully, reliably written to the physical device. It provides performance improvement with both synchronous and asynchronous writing policies.

When in synchronous mode, the completion request doesn't wait for the change to be made permanent on the device, it merely waits for the acknowledgement from the journal.

In asynchronous mode, the journal helps providing data loss window by ensuring the user will not lose data if the changes are committed to the journal before the window is expired.

The recovery journal has two parts. One is stored on the physical device and the other in memory to serve as a buffer. When entry is added to the journal, it is processed by the part in memory and is regarded as an active block. An attempt to commit the block to the device is made, however, the device might be locked by another commit that's in progress which makes the commit queue. Every successful commit will wake others waiting after it is completed.

2.3.3 Block map cache

Block map exists in VDO volume to maintain the mapping of logical blocks to physical blocks and managed as pages with each page holding 812 entries of logical blocks. The entire block map is kept on disk, since it can be rather large.

Block map cache is a subset of the entire block map that is kept in memory for performance increase. If request to access a block comes to VDO, it will check if that block is in the block map cache. In case it doesn't it needs to read the relevant page and store it in a cache. In case the request was write, it is written in the block map cache and only participates to the on-disk part later.

The block map is a cause of one of the requirements on physical space. It usually consumes about 1.25GB per 1 TB of saved stored physical data. The subset that's kept in memory is much smaller, 128MB by default and is tunable by `-vdoBlockMapCacheSize`.

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The 128MB can cover about 100GB of logical blocks. However if users logical space is larger than 100GB and their workload is so random that it doesn't cache pages, user can observe great performance hit. In case the block map cache is full, therefore runs out of free pages and a request comes for a page that's not contained in the cache, VDO needs to first discard some page from the cache, write it on disk and just after then load the desired page. It is obvious that this cycle is very time expensive and therefore users are encouraged to increase block map cache size if the preconditions for cache tiering are met.

2.3.4 VDO threads

2.3.5 UDS index

UDS index is a structure designed specifically to identify duplicate data using hash fingerprints of data blocks. It exists in VDO to provide deduplication advice for effective deduplication. Instance of UDS index is not vital for VDO block handling. In case of losing the index, the VDO still manages blocks and stores and compress data, only without deduplication. Even in the event of index becoming corrupted, there are different mechanisms in place to assure data correctness, so user can discard the index and start building a new one.

Also, updating index is costly, so VDO is trying to minimise the updates. That is a reason the index can contain references to blocks that are no longer present in data. Those blocks are called stale blocks.

2.4 Tunables

2.4.1 VDO write policies

VDO can operate in either synchronous or asynchronous mode. By default VDO write policy is set to *auto* which means the module decides automatically which write policy to enforce. The main difference is in the approach if the block is written immediately or not. The obvious consequence is that if a system fails while VDO performs asynchronous write, user can lose data.

In synchronous mode, the block is temporarily written to an allocated block and acknowledges the request. After completing the

acknowledgement, it attempts to deduplicate the block. In case it's a duplicate, block map is updated in a way that the logical block points to the physical block that's already written and releases the temporal block. If the block is not a duplicate, *kvdo* updates the block map to make the temporarily allocated physical block permanent.

In asynchronous mode, instead of writing the data immediately, only physical block allocation and acknowledgement of the request is performed. Next, VDO will attempt to deduplicate the block. If the block is a duplicate, the module only updates its block map and releases the allocated block. If the block turns out to be unique, it is then written to the allocated block and the block map is updated.

2.4.2 Block map cache size

2.4.3 VDO threads

2.4.4 Discard size

3 Benchmarks

3.1 fs-drift

Fs-drift is an open-source benchmark developed specifically for testing heavy workload and aging performance. Being implemented in Python, it is very easy for users or contributors to add new features or change the benchmark behavior to their needs. For testing performance of VDO, several new features were added.

For performance testing of VDO, new features and behavior needed to be implemented to fs-drift to enable more precise control over IOs and testing process.

3.1.1 Compressible data generator

While testing compression and deduplication technology as VDO, data generated for testing need to be specifically shaped. The benchmark needs to be able to generate the testing data in a way that corresponds to examined cases. A restriction for VDO testing is that the repeating patterns in compressible data cannot be composed entirely of zeroes, because the way VDO deals with zero blocks (see, Zero blocks elimination). For this reason, new parameter was added to fs-drift, that enables the user to produce buffers using *lzdatagenerator* with specified compressibility.

The parameter works as follows:

- `-c` | `--compression-ratio`, number that is a desired compress ratio, e.g. 4.0 is 1/4.0, therefore compressibility will be 75% (default 0.0)

This feature was implemented using alternative IO buffer behavior which works with another open source project called *lzdatagen*.

LZ data generator (i.e. *lzdatagen*) is a simple but powerful tool for generating data with desired compressibility. In the simplest use cases, user only specifies the desired size and compress ratio and obtains data with the exact qualities.

Usage is:

- `./lzdatagen -size SIZE -ratio RATIO`

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If there is a compression ratio set other than 0.0, the buffer is filled using `lzdatagen` call with the desired compression ratio. Otherwise the buffers are filled the same way as in previous versions of `fs-drift`.

This simple but powerful feature now empowers the benchmark user to specify the compressibility of written data and therefore makes the user able to measure performance of any technology that deals with compression feature such as ZFS or VDO.

3.1.2 DirectIO

When researching behavior of random operations in `fs-drift`, file system cache can often skew considerable amount of measurements.

The system cache considerably affects both writes and reads, and the effect is mostly visible with random operations. In `fs-drift`, *fsync* time was taken into the measurement to get the real request completion time. However, the system cache successfully serialises the requests, so at the time of `fsync`, they are written sequentially.

To battle this effect, option to use direct IO was added. When passing `os.O_DIRECT` flag to the `os.open()` call, the UNIX based systems require memory alignment to the underlying device so all the operations had to be refactored into being aligned.

3.1.3 Rawdevice

While file system can be installed on a VDO layer (and there is an increasing number of users which do), it is important to have an option to test VDO block device also without the file system to get more precise measurements. File systems can have considerable impact on performance and can skew results in ways that make it hard to clearly observe VDO impact on overall performance.

Rawdevice mode was added, that enables `fs-drift` to run block-wise on a given device instead of working with files on a file system.

This option is triggered as follows:

The parameter works as follows:

- `-R | -rawdevice`, set path of the device to use it for rawdevice testing (default "")

3.1.4 Random discard operation

With thinly provisioned technology being increasingly relevant, it is interesting for researchers to also test performance of a block discards. Discard command could be passed either from the file system or an application to let the underlying device know that the particular block is no longer occupied and can be returned to the block pool.

In Linux, available command for block discard is *blkdiscard*. User can specify the offset and length to be discarded, making it very easy to write an operation type for fs-drift.

If the user of fs-drift wants to test discard speed, he can specify so in the configuration file along with its probability. When the event of discard is triggered, fs-drift works similar as with random writes, but instead of producing buffer and writing, it's using *blkdiscard* with random offset and specified request size to discard blocks.

3.1.5 Random map

When computing offset for random operations, it might not enough to just generate random number. Sometimes it is beneficial to administer IOs only to unused blocks, ensuring no overwriting takes place and all the free blocks will eventually be used.

For this purposes a feature to keep track of unused offsets was added to fs-drift. The random map is generated before the test as a shuffled list of possible indices, to save time while the workload is in progress.

The user should be wary of the fact that if the test runs out of the random map, it is recomputed again and will start to overwrite data.

The parameter works as follows:

- `-r | --randommap`, if true, use random map to get random offsets (default False)

3.1.6 Performance measurement

In fs-drift, performance is measured by saving a time stamp before invoking the IO operation and storing the time stamp difference after the operation was finished. However, with this type of measurement,

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it is important to make sure the time stamping is as close to the actual IO operations as possible.

In previous versions, the time measurement was the same for every IO operation, which made some of the measurement inconsistent, e.g. taking into the measurement the time to fill buffer etc.

This problem was removed by moving the time stamps inside the functions, providing more precise control over the timing of events.

Another small feature added by switching to *perf_counter()* as a tool to log time instead of *time()*.

3.1.7 Data reporting

In previous versions, several problems in measurement reporting had to be addressed.

One of the problems was the data storage. In older versions, data were stored in-memory which posed two problems when running very long tests:

- RAM consumption
- Lose of data after benchmark failure

The new approach that was installed uses a file predestined on a stable device (i.e. system device). Every time the measurement is made, an entry is appended to the file. This means that even after many days of testing, the memory of a system is not cluttered. On top of that, if the system or benchmark fails, there is still some data to be retrieved from the file.

Second problem that caused noisy performance data in the previous versions was the use of response times as units of performance measurement. However, since there could be a large range of file sizes, this unit introduces noise, because larger files will take longer to process in what could seem like a decreased performance.

Therefore, the option to store bandwidth was added as a new feature. Bandwidth is measured as a total IO size divided by the time of completion. This way, variability of request size will not be affecting the data points.

3.2 FIO

Flexible Input/Output tester is a workload generator known for its flexibility and large base of users and contributors. It is an excellent benchmark for testing block devices and file systems since it gives users very precise control over the workload.

3.2.1 for testing VDO

4 Testing methodology

This chapter presents used testing hardware, preparation of testing environment and performance measuring methodology.

4.1 Testing environment

While testing performance, usage of clean testing environment is strongly encouraged. In time of testing, no other applications should run in the environment to ensure low noise levels. Running tests on clean installation of OS is preferred to ensure no performance impacts caused OS aging, memory shortage, etc.

For this thesis, testing was conducted on instances of RHEL-8.1 and RHEL-8.2 to gain access to the most recent features. Tuning options for the systems were set to *throughput – performance*. Other options for the OS are left to be default.

Storage stack for testing purposes is always prepared by executing a sequence of LVM commands. For the simple tests, one volume group and one logical volume was used to be a block device for VDO layer.

The storage stack can be tested either as a raw device, or file system can be installed on top of it when working with files, or relationship between stack and file system needs to be examined.

It is important to create a fresh instance of stack before the test to ensure stable testing conditions. Also, before every test, we *sync* and *dropcaches*.

4.2 Testing hardware

Testing for this thesis was conducted on multiple machines provided by Red Hat company. I will introduce testing systems which will be used for multitude of tests with or without the VDO layer installed. These machines were chosen by their computing power, provided memory and by useful storage hardware they are equipped with. These machines are stable systems used by Red Hat Kernel Performance team for regular testing.

4.3 Supermicro X11SPL-F

This machine is used for regular testing of VDO and other complex technologies in Red Hat Kernel Performance team. It's equipped with 4 10 TB SAS rotational drives and one 220 GB SATA SSD for tests that require LVM Cache. The system is always installed on an additional SSD. This machine is equipped with enough memory to handle large VDO volumes.

Machine 1	
Model	Supermicro X11SPL-F
Processor	Intel Xeon Silver 4110
Clock speed	2.10 GHz (8 cores)
Memory	49 152 MB
Testing Hard Drives (4x)	
Model	WD HGST Ultrastar
Capacity	1 TB
Interface	SAS 12 GB
Type	Rotational HDD
Logical sector size	4096 B
Physical sector size	4096 B
Testiting SSD (for LVM cache)	
Model	Micron 5100 MTFD
Capacity	240 GB
Interface	SATA 6 GB
Type	SSD
Logical sector size	512 B
Physical sector size	4096 B
System disk	
Model	SuperMicro SSD
Capacity	126 GB
Interface	PCIe Gen3 x4 Lanes
Type	SSD
Logical sector size	512 B
Physical sector size	512 B

4.4 Data processing

5 Performance of VDO

5.1 Empty VDO

When preparing VDO volume for testing it is important to notice that a logical space of a fresh instance of VDO is not yet fully allocated. Only after writing data, the volume becomes progressively more allocated. Every new subsequent block of data that is written to VDO has to allocate one to four new blocks. This could affect writing performance of new VDO volume.

To examine this effect, random write workload can be used on a new instance of VDO. Results can be compared to a performance of a fully allocated VDO volume or to a device without VDO.

To obtain fully allocated, but empty VDO volume, it is sufficient to just write one zero byte to every VDO sector. One VDO sector is 812 VDO blocks (default block size in VDO is 4096), so we'll write a zero byte every 812×4096 bytes.

5.2 Half empty VDO

5.3 Block map cache

As mentioned in chapter 2, block map cache is an internal VDO structure that keeps part of the journal in memory to provide better performance. Its default size is 128 MB, which is XXX pages, that covers about 100 GB worth of data.

This could pose a performance problem in case the logical space is large enough and the workload access the space in a way the block map cache is tired out. If the block map cache fills up, (runs out of free pages), and there is a write request to a non-cached page, the cache is forced to discard one page from its pool to make room for the relevant page. This operation is very costly and this could become a bottleneck for VDO performance.

To test this effect, we can use random write workload on an instance with sufficient and insufficient cache size. The parameter to tune cache size in VDO is `-blockMapCacheSize=BYTES`.

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To ensure the workload is truly aggressive, large file size and completely random write is used so the test makes lots of requests in a short amount of time and the effect of caching pages could be seen.

5.4 VDO threads

5.5 Discard size

5.6 Steady state testing

5.7 Testing on different architectures

5.8 Journal performance

5.9 Testing with distributed file system

6 Conclusion