IOArbiter: Dynamic Provisioning of Backend Block Storage in the Cloud

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Abstract—With the advent of virtualization technology, cloud computing realizes on-demand computing. The capability of dynamic resource provisioning is a fundamental driving factor for users to adopt the cloud technology. The aspect is important for cloud service providers to optimize the expense for running the infrastructure as well. Despite many technological advances in related areas, however, it is still the case that the infrastructure providers must decide hardware configuration before deploying a cloud infrastructure, especially from the storage’s perspective. This static nature of the storage provisioning practice can cause many significant problems in meeting tenant requirements, which often come later into the picture. In this paper, we propose a system called IOArbiter that enables the dynamic creation of underlying storage implementation in the cloud. IOArbiter defers storage provisioning to the time at which a tenant actually requests a storage space. As a result, an underlying storage implementation, e.g., RAID-5/6 or Ceph storage pool with (6,3) erasure coding, will be materialized at the volume creation time. Using our prototype implementation with OpenStack Cinder, we show that IOArbiter can simultaneously satisfy a number of different tenant demands, which may not be possible with a static configuration. Additionally the built-in QoS mechanisms, including admission control and dynamic throttling, help IOArbiter system mitigate a noisy neighbor problem among tenants.

I. INTRODUCTION

With the advent of virtualization technology, cloud computing materializes on-demand computing. A tenant can create a virtual infrastructure based on their exact needs in a much shorter amount of time and the amount of provisioned resources can be adjusted anytime from anywhere by the tenant. The capability of dynamic resource provisioning is a fundamental driving factor for users to adopt the cloud technology. The aspect is also important for cloud infrastructure providers in order to optimize the overall expense (CapEx/OpEx) for running the infrastructure.

For enterprise storage solutions, vendors drove an appliance-based model that typically provide proprietary software and customized hardware to support a specific class of applications, e.g., database, and/or a specific layer of storage stack, e.g., NFS storage, SAN block storage, etc. However, since many different tenant/storage applications will share the same infrastructure in the cloud setting, the underlying storage implementation should be able to be adapted for active tenants. Unfortunately, despite the fact that many recent technological advances have been made in virtualizing compute, network, and storage resources in the cloud, it is still the case that the infrastructure providers should decide hardware configuration before deploying a cloud infrastructure, especially from the storage’s perspective. For instance, the OpenStack Cinder [10] service, which governs block storage management tasks, mandates a preconfigured "storage implementation" [1] before the operation, e.g., through local RAID configuration, vendor appliances/solutions, etc. In a multi-tenant cloud environment, in particular, the static nature of the storage provisioning practice can cause many significant problems for meeting tenant application requirements, which often come later into the picture.

Table I shows an illustrative example. We consider two applications. One is a Virtual Desktop Infrastructure (VDI) application and provides a virtual desktop environment for corporate employees through VMs in the cloud. It requires reliable storage, and consequently demands triple (3x) replication strategy, which is a common industry practice. The other application, vCDN, is a virtualized Content Delivery Network (CDN) application. Unlike the VDI application, vCDN implements triple redundancy in its application layer. In this case, since the application replicates data across three data centers, it is not necessary for underlying storage systems to provide any additional redundancy. Suppose that we first deployed the VDI application to the cloud, and after some time deploy the vCDN application in the same cloud infrastructure. Since the architects only knew about the VDI application when they design the infrastructure, they implemented storage systems based on the triple replication strategy. Even though the vCDN application, which comes later into the picture, does not require an additional redundancy, it needs to be deployed into the same infrastructure. As a result, we end up with wasting a lot of storage space, i.e., 12x vs. 6x in the table. In many practical scenarios, it is not easy to avoid this kind of situation due to the rigid nature of storage services. However, if

| Application                      | A single storage implementation | Dynamic provisioning |
|----------------------------------|---------------------------------|----------------------|
| VDI that requires 3x redundancy from underlying storage systems | 3x                             | 3x                   |
| vCDN that implements 3x redundancy in the application layer. | 9x                             | 3x                   |
| Total Storage Overhead           | 12x                             | 6x                   |

TABLE I
A CASE OF AN INEFFICIENT UTILIZATION OF STORAGE CAPACITY.

In this paper, we use the term "storage implementation" as a software/hardware configuration on top of which a logical volume will be created. For instance, it can be a traditional RAID if one uses local disks for cloud block storage, or a Ceph storage pool if one relies upon such a system.
we can somehow configure the underlying storage parameters dynamically, e.g., this problem might be resolved as depicted in Table I. In this particular example, total storage overhead of a single storage implementation is twice as much as the ideal case.

In this paper, we propose a system called IOArbiter that enables the dynamic creation of underlying storage implementation in today’s cloud. IOArbiter defers the implementation of underlying storage to the volume creation time, i.e., the time at which a tenant actually requests a storage space. To avoid humongous design space, a cloud infrastructure provider may define a customized set of storage implementation types so as to incorporate a range of performance and reliability levels, e.g., RAID-5 or 6 with a minimum of 200 IOPS, Ceph with (6, 3) or (10, 4) erasure coding, etc. and use them with IOArbiter system. When a tenant request, e.g., volume creation, is come into the system, IOArbiter analyzes the request and automatically creates a necessary storage implementation if it is not yet available in the infrastructure, e.g., RAID-5 with 6 disks or Ceph with (10, 4) erasure coding, etc. As a management layer of cloud block storage services, IOArbiter has a number of useful features, including a) an ability to perform garbage collection, e.g., reclaiming unused space and/or a storage implementation, b) an admission control and dynamic throttling mechanism that enables per-VM IOPS allocation, and c) a containerized control plane for effective maintenance.

We implemented an IOArbiter prototype with OpenStack Cinder [16]. Our preliminary evaluation result shows that IOArbiter can simultaneously satisfy heterogeneous tenant demands, which may not be even possible with a static storage implementation. Moreover, IOArbiter has a negligible overhead in terms of scheduling operation.

The rest of the paper is organized as follows. Section II gives some basic information on OpenStack Cinder and further motivates the problem. Section III then describes design rationales and overall system architecture. The detailed description of how we implement our system with OpenStack is presented in Section IV. We provide our preliminary evaluation results with our prototype system in Section V our investigation on related work in Section VI and conclude the paper.

II. BACKGROUND AND MOTIVATION

In this section, we provide a brief overview on the block storage management layer in the cloud and present several exemplary problems caused by the static nature of storage provisioning practices.

A. Cinder: virtualized block storage management layer

In this paper, we assume a cloud environment based on OpenStack open source software in order to manage underlying physical computing resources. There exist many alternatives including both proprietary [2]. [15]. [7] and open source solutions [3]. Nonetheless, OpenStack is chosen by us since it is not only an open source solution, but is also supported by a large community behind it. OpenStack has a block storage management layer, Cinder [16], which is a primary focus of this paper. Cinder governs a control path of cloud block storage, e.g., creating/deleting logical volumes for tenant VMs on the provisioned storage implementation, connecting/disconnecting them to/from VMs, etc.

Cinder service is comprised of several sub-components. The cinder-scheduler typically runs on the OpenStack cluster’s controller nodes. When a block storage request is issued by users through REST API calls, cinder-scheduler determines which storage node should handle a given request (e.g., volume creation/deletion). In each storage node, one or more cinder-volume services will be instantiated, take the request object, and actually perform the designated task. All communications among cinder-scheduler and cinder-volume go through a common message bus, e.g., RabbitMQ [18]. ZeroMQ [4], etc. When cinder-volume receives a request, manipulating logical volumes such as creating/deleting a volume is performed through a volume-driver specific to the underlying storage implementation. For instance, a RAID configuration based on local disks typically relies upon the LVM driver implementation. Some open source distributed storage systems provide their own drivers, e.g., Ceph RBD. Vendor appliances have their own driver to properly interact with proprietary software and hardware. For the plumbing part, i.e., connecting/disconnecting a logical volume to/from VMs, Cinder also supports different types of transports, e.g., iSCSI, Fibre channel, etc. Additionally, Cinder provides a plug-in framework for cinder-scheduler so that a developer can implement a customized scheduler filter. IOArbiter implements its own volume placement strategy using the scheduler filter interface.

B. Growing pains in cloud block storage: example cases

In addition to the motivating example given in Section I our organization have faced several problems due to the static nature of the storage provisioning practice. Here we illustrate some of them to further motivate the problem.

Reconfiguring storage. Our IT team provides a disk array preconfigured with RAID-6 with arbitrary internal partitions. There were no problems in the beginning. Later, however, one of our development teams wanted to deploy a virtualized CDN application that replicates its data across multiple datacenters in the application layer. In this case, using RAID-6 for the application is a waste of storage space since it will be unnecessarily replicating data internally. It was hard for the IT team to change it easily since other tenants are already using the array.

Meeting multiple performance requirements. A storage array that has 24 SATA HDDs is configured as JBOD and used by one application that does not require redundancy on the storage layer. Later, another application comes to the cloud and requests a minimum of 500 IOPS for its VMs’ block

2 Some of these stories are slightly modified from the real events for more accessible description.
3 Just a Bunch Of Disks
4 I/O operations per second
storage traffic. Unfortunately, its workload is mainly composed of 4 KBytes random read/write, 50% each. Since the entire disk array is configured as JBOD and a single disk can support ~200 IOPS for this type of workload. If the underlying storage implementation was RAID-5 or 6 with multiple disks, the requirement might be supported more easily. So they have no other choice than to construct a software RAID inside a VM. Unfortunately, however, the disks in the array were all partially occupied by other VMs.

**Isolation from other tenants.** A storage array is configured as RAID-6 and multiple tenants start to utilize the space. After some time, a tenant from a government organization requests a physically isolated storage for their data. Despite the fact that there are sufficient storage space remained in the disk array, it was not trivial to carve out some of the disks for a new tenant given that SLAs require 24/7 uptime.

The cases including all of the above-mentioned scenarios, but not limited to, can be benefited by IOArbiter-like systems that can dynamically configure and change the underlying storage implementation at runtime.

### III. IOArbiter Design

#### A. Design principle

IOArbiter is designed based on two fundamental principles: *late binding* and *non-intrusiveness*.

**Late binding.** To enable dynamic provisioning of a storage implementation, IOArbiter adopts the late binding principle, which is a popular computer programming mechanism. Inspired by this principle, a storage implementation will be bound to the cloud infrastructure at the request time, i.e., volume creation time. Storage medium may be provided as a bunch of raw disks or with a state ready to be configured, e.g., a vanilla Ceph installation without any configured storage pools. Then, any relevant storage implementation will be created when necessary, e.g., a RAID for the former and a storage pool for the latter example.

**Non-intrusiveness.** Since IOArbiter is aimed to be deployed in production clusters, it is desirable to minimize probable impacts on existing OpenStack components. We make a couple of important decisions for this purpose. First, we implement IOArbiter as a filter and driver for the Cinder service rather than making the system as a separate stand-alone service. With this approach, IOArbiter can naturally integrate with existing components, and consequently minimize potential incompatibility problems. Second, we exploit a container technology to isolate a newly created storage implementation. This decision ensures a dedicated agent per storage implementation, and thereby isolates the instance from other storage implementations. As a result, the system administrator can easily enable/disable the storage implementation as needed. Most failures in a given storage implementation will not affect other storage implementations.

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Figure [1] illustrates IOArbiter system architecture. The system is comprised of several components including Scheduler, StateDatabase, StorageBroker and StorageManager. When a user request arrives at the system with a storage specific requirement, e.g., a triple replicated volume with 100 minimum IOPS, Scheduler first checks the resource availability based on the data from StateDatabase and decides who should handle the request, i.e., either StorageBroker or StorageManager. If a new storage implementation is required by the request due to the absence of resources, StorageBroker will take the request and create a new storage implementation. Otherwise, i.e., if there exists a storage implementation that can support the request, Scheduler will route the request to one of the available StorageManager. A storage implementation can be a RAID configuration based on local disks, a storage pool based on a distributed storage systems like Ceph [23], or any storage vendor solution. When StorageBroker creates a storage implementation, it will additionally create a StorageManager associated with the storage implementation. StorageManager will execute actual storage commands, such as creating/deleting a logical volume at a storage implementation, attaching/detaching it from VMs, etc. It is worth noting that IOArbiter uses container technology to isolate the newly created control path of StorageManager.

Once instantiated, StorageBroker and StorageManager instances will report their states to StateDatabase so that Scheduler can perform the scheduling actions. The report message from StorageBroker has a set of information about raw resources for which the StorageBroker is responsible. For instance, it can be the number of disks, disk types, and mediums in case of a software RAID-based storage implementation. In contrast, the report from StorageManager contains more specific information of the storage implementation. It includes the number of logical volumes already created in the storage implementation, total performance budget and allocated resources, capacity status, etc.
C. Performance isolation

IOArbiter is intended to be deployed for multi-tenant cloud environments. In this context, performance isolation is an important issue. IOArbiter provides two features – admission control based on offline profiles and dynamic throttling based on runtime characteristics.

Admission control. When a new storage implementation is created, a containerized StorageManager will be created along with it. At that time, IOArbiter ensures that a new StorageManager has a total performance budget for that particular storage implementation. For instance, if the storage implementation is based on a single SATA HDD, IOArbiter allocates ~200 for the worst-case 4k-block IOPS budget. After that, whenever a new volume creation request comes into the system, StorageManager manages budgets and inform the remaining budgets to StateDatabase. This will ensure that, if a budget is full for a given storage implementation, no more requests will be issued to the corresponding StorageManager.

Algorithm 1: Dynamic Throttling

```
1 Set minimum IOPS for each volume i (R_i);
2 By default, R_i = 0;
3 Set control interval: M;
4 while wait M seconds do
5     is_throttling = false;
6         foreach volume do
7             collect current IOPS;
8             if current IOPS < minimum IOPS then
9                 throttle each volume i by R_i;
10                is_throttling = true;
11             else
12                 continue; /* do nothing */
13         end
14     if is_throttling == false then
15         release all throttling;
16     else
17         continue; /* do nothing */
18     end
19 end
```

Dynamic throttling. Although IOArbiter allocates performance, e.g., IOPS, based on the budget, it might be the case that some resource interference still happens among the allocated volume traffic. IOArbiter provides a dynamic throttling mechanism to mitigate the problem, as shown in Alg. 1. IOArbiter monitors a runtime statistics (i.e., current IOPS) of each volume (at line 7) and, if the performance requirement (i.e., minimum IOPS) of a certain volume is violated (at line 8), it suppresses other flows sharing the same storage implementation based on their worst-case requirements (at line 9). If no performance requirements are violated, throttling actions will be disabled (at line 16).

D. Discussion

Garbage collection. Since IOArbiter encourages dynamic provisioning of storage implementation, there exists a concern on resource fragmentation. To mitigate this problem, IOArbiter has a notion of periodic garbage collection mechanism. Based on the mechanism, IOArbiter is able to reclaim unused storage space, if any, and rebalance the skewed data in already deployed distributed storage systems.

High available and scalable service. IOArbiter system belongs to a control plane of cloud block storage. In a large scale cloud infrastructure where 1000s of nodes or more can be deployed, it is important to make a service both highly available and scalable. Making a centralized gateway to be highly available, balancing incoming traffic load uniformly across the available resources, and handling partitioned service resources are classic topics of distributed systems. We do not attempt to make any contribution in the above-mentioned problem space. Instead, IOArbiter could exploit an external service that is dedicated to these functions, such as Pacemaker [17].

IV. IMPLEMENTATION OF IOARBITER SYSTEM

We have implemented an IOArbiter prototype with OpenStack Cinder service [16]. The integrated system is described in Fig. 2. The IOArbiter sub-components are mapped onto Cinder components. A tenant request is described as a Cinder volume-type, which can have a set of user-defined key-value pairs, e.g., {redundancy=5, min-iops=100, Iosize=4K…}. Cinder has an RESTful API interface (cinder-api) and the communication between clients and cinder-api is through a message queue service, e.g., RabbitMQ [13], ZeroMQ [4], etc. Scheduler is mapped onto cinder-scheduler and implemented as one of its filters. StorageBroker and StorageManager each are mapped onto cinder-volume with a different mode of operations – cinder-volume(broker) and cinder-volume(provisioned) – and implemented as a separate driver[3] In Fig. 2 as an example, we present a software-based RAID configuration based on local disks available in a single storage node. It should be noted that IOArbiter can support other types of storage implementation such as configuring a storage pool for Ceph, etc.

As discussed in Section [11] IOArbiter exploits a container technology to isolate a newly created control path. We use the Docker container [3] for our prototype implementation. The cinder-volume uses a local configuration file (cinder.conf) to configure and maintain its internal states. IOArbiter inserts an additional information in that file for our admission control

5For instance, an extended version of LVM driver.
mechanism. When a containerized `cinder-volume` (i.e., `cinder-volume(provisioned)`) is created, `StorageBroker` (i.e., `cinder-volume(broker)`) will insert pre-computed performance budget into a `cinder.conf` file inside the container. Those budget numbers are based on offline profiles and specific to a given `storage implementation`. After that, but accounting operations are done by `cinder-scheduler` based on the reported information from the containerized `cinder-volume` service. Dynamic throttling service will be instantiated inside each container, run as a daemon process, and periodically collect block device performance in case of software-RAID based `storage implementation`. When an SLA violation is observed, the service throttles all other storage traffic sharing the `storage implementation`.

V. PRELIMINARY EVALUATION

A. Setup

We ran an experiment in an OpenStack cluster that has 11 nodes (servers). For IOArbiter, we carve out two storage nodes, i.e., nodes where `cinder-volumes` are running, and other nodes are operated normally under a single OpenStack installation. For the two nodes, we install the IOArbiter driver for `cinder-volume` services and expose raw local disk drives to IOArbiter system so that it can create a custom `storage implementation` based on the disks. The two nodes have 10 and 7 local HDDs respectively, each of which has 1TB of storage capacity.

B. Dynamic provisioning and meeting multiple requirements

We design an experiment that can show the benefits of dynamic provisioning of a `storage implementation`. Through the experiment, we aim to demonstrate the followings:

* Simultaneously meet a diverse set of tenant requests within a tight resource budget. Each request has a different performance and reliability level.
* Meet performance requirements of allocating an IOPS in a per-volume basis.
* Perform a garbage collection for higher resource utilization.

For the experiment, we configure three different `volume types` (Table II) and use the input sequence described in Table III. Each request is issued to the cluster every 90 seconds. The result is reported in Fig. 3. The figure clearly shows that IOArbiter can dynamically create `storage implementations` to satisfy heterogeneous requests (Req.#1, #2, and #3). In addition, it demonstrates that IOArbiter can allocate IOPS correctly (Req. #7 failed due to the budget constraint). In detail, our offline profiles tell us that we could use 200 IOPS (for 4k-block random read/write) per HDD as a total performance budget. So, a RAID-6 based on 4 disks (on node 2) has 400 IOPS of a total performance budget, and consequently the fifth trial with a type-2 request (Req. #7) failed; notice that a type-2 volume creation request comes with 100 IOPS.

After all 7 requests were processed, we also evaluated the garbage collection capability of IOArbiter system. In a software-RAID based implementation, we built a mechanism that could reclaim unused storage space, especially when there are no logical volumes in a given `storage implementation` for some amount of time. After deleting volumes, IOArbiter successfully reclaimed disks and each `storage implementation` returned to a raw disk pool. Although not evaluated in this paper, it is worth noting that the garbage collection mechanism can be useful to other types of `storage implementation`, e.g., distributed storage systems such as Ceph. In case of Ceph, the garbage collection may trigger rebalancing operations to alleviate a skewed data distribution in the cluster.

C. Scheduling overhead

IOArbiter has an additional intelligence for determining which host can satisfy a given requirement. Nonetheless, it turns out the overhead incurred by IOArbiter system is negligible, i.e., only about 5~6 milliseconds of latency will be added for `cinder-scheduler` to determine the eligibility of a storage host.

VI. RELATED WORK

As cloud services boom, attention is drawn to providing users with block storage. Amazon Elastic Block Store (EBS) [1] and OpenStack Cinder [16] provide persistent block level storage volumes with virtual instances, usually via iSCSI [19]. For `cinder-scheduler`, Yao et al. design and implement a new scheduling filter with the ability of I/O throughput filtering and weighting to meet IOPS requirements [26], and propose a new block storage resource scheduling algorithm called MVBFD [27].

To the best of our knowledge, IOArbiter system is novel for its dynamic provisioning of a `storage implementation` in the area of cloud block storage. Nonetheless, we can easily observe dynamic operations in modern distributed storage systems. For instance, Ceph storage cluster can dynamically grow, shrink, and rebalance data along with the changes in underlying resources, e.g., # of OSDs [23], [25], [24]. ASCAR [11] autonomously controls I/O traffic from storage clients using a rule based algorithm called SHARP, which uses the congestion window and rate limit, in order to increase the bandwidth utilization and reduce speed variance.
IOArbiter implements a couple of simple, yet powerful, mechanisms to provide QoS. There exists an extensive body of research in the area of providing performance isolation and delivering guaranteed performance to tenants in today’s virtualized datacenters. Most of them are complementary to IOArbiter system in nature. Gulati et al. proposes several approaches [9], [8], [10] and implements them in VMware ESX hypervisor. mClock [9] proposes an IO scheduling algorithm in a hypervisor for per-VM QoS that supports reservation, limits, and shares. PARDA [8] provides proportional-share fairness to multiple hosts sharing a single storage array; it detects overload via latency measurements, and then adjusts per-host issue queue lengths using flow control very similar to FAST TCP [22]. SRP [10] proposes a hierarchical IO resource allocation system that support the logical grouping of related VMs into hierarchical pools; SRP controls IO reservations, limits and proportional shares at VM or pool level in an environment where VMs running multiple hosts are accessing the same storage. Elnably et al. [6] proposes a scheduling algorithm called reward scheduling to provide QoS in a multi-tiered storage system that uses both SSD and HDD. For key-value cloud storage, Pisces [20] provides per-tenant weight fair sharing and performance isolation, and Pileus [21] allows applications to use a choice of consistency guarantees with latency targets for consistency-based SLAs.

Tangentially related is a body of work that provides a QoS-aware block device interface to tenants in the cloud. Lin et al. [12] proposes a block storage system design called FAST to minimize interference among tenants; read operations are redirected when different types of workloads (i.e., random and sequential reads) are co-located. Mesnier et al. [13] proposes an IO classification architecture with a slightly-modified block interface in order to provide differentiated storage services. Blizzard [14] extends the simple block interface for high IO performance, mapping each virtual driver to multiple backing physical disks, and providing high-level software abstractions such as replication and failure recovery.

VII. CONCLUSION AND FUTURE WORK

We present a system, called IOArbiter, that can dynamically provision an underlying storage implementation for cloud block storage services. IOArbiter defers the storage provisioning process to the time at which a tenant actually requests a storage space. The late binding can offer high flexibility to the cloud service providers, thereby resulting in higher utilization. IOArbiter implements two mechanisms, i.e., admission control and dynamic throttling, to provide QoS on performance among tenant applications. Through preliminary evaluation, we demonstrate that IOArbiter can satisfy heterogeneous tenant requests even with considerably limited storage resources and perform a proper admission control for allocating IOPS per volume.

Much work remains. We plan to integrate IOArbiter system with an emerging JBOD (Just-a-Bunch-Of-Flash) device and other distributed storage systems in the near future. Its QoS mechanism must be evaluated further thoroughly, even if our preliminary evaluation result looks promising.

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