Efficient and agile storage management in software defined environments

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The IT industry is experiencing a disruptive trend for which the entire data center infrastructure is becoming software defined and programmable. IT resources are provisioned and optimized continuously according to a declarative and expressive specification of the workload requirements. The software defined environments facilitate agile IT deployment and responsive data center configurations that enable rapid creation and optimization of value-added services for clients. However, this fundamental shift introduces new challenges to existing data center management solutions. In this paper, we focus on the storage aspect of the IT infrastructure and investigate its unique challenges as well as opportunities in the emerging software defined environments. Current state-of-the-art software defined storage (SDS) solutions are discussed, followed by our novel framework to advance the existing SDS solutions. In addition, we study the interactions among SDS, software defined compute (SDC), and software defined networking (SDN) to demonstrate the necessity of a holistic orchestration and to show that joint optimization can significantly improve the effectiveness and efficiency of the overall software defined environments.

Introduction

Software defined environment and software defined storage

Rapidly changing IT (information technology) environments are posing a challenge, in particular to the traditional processes of storage management and provisioning. Massive data growth is being compounded by less predictable and increasingly diverse needs in terms of usage of that data. In such conditions, the long software installation and hardware configuration cycles dependent on manual and expert operations invariably lead to poor resource utilization and lack of responsiveness from an application perspective. More generally, trends such as reduced application deployment time, increasing use of commodity components, and simplification of IT operations are all reflections of important business needs. In terms of storage, this means keeping investment and exploitation costs from rising overwhelmingly with the growth of data, while at the same time increasing agility to respond to changing business demands in a cost-effective manner.

The advent of software defined environments (SDEs) comes as a response to these needs. In essence, an SDE automatically allocates workloads to the most suitable set of infrastructure resources, dealing with potential heterogeneity across both workloads and resources, and continuously optimizes such allocations to account for changes in workload needs and resources.

Software defined storage (SDS) refers broadly to the evolution of storage systems to meet the needs of SDE, affecting the design of control and data planes. For instance, on the control plane, traditional storage systems can expose interfaces to automate the provisioning of their resources. On the data plane, workloads can optimize their data accesses through explicit interactions with the storage system, as discussed in [1]. Finally, data plane functions may be moved altogether into a software stack that can be instantiated on commodity hardware to achieve lower costs, as discussed elsewhere [2].

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In the very dynamic context of SDEs, storage is however a notable exception: whereas failures of compute or network resources can be mitigated by repeating computations or resending data, stored data cannot be re-created in such a straightforward manner. Furthermore, data may have to remain persistent after the lifecycle of the workload. Storage resources must therefore offer the means to satisfy a certain level of data protection, in addition to, for instance, availability or performance levels also applicable to the other types of resources. Moreover, depending on its size or sensitivity, persistent data will also limit the mobility of workloads that otherwise encapsulate their needs in a form operable by various infrastructure providers.

Software defined storage objectives

An analogy with software defined networking (SDN) is helpful to reach a more formal definition of the objectives associated with SDS. SDN is aimed at providing a software implementation for some or all of the networking control plane in standard servers, and use of a programmatic interface to the data plane, which itself may even be implemented in software [3, 4]. The SDN approach can therefore be divided into two dimensions, both of which apply to SDS as well, as illustrated in the following examples: (1) a horizontal dimension of global optimization across nodes, where control plane functions shift from a fully distributed model to a centralized model in order to enable global optimization across the nodes; and (2) a vertical dimension of the level of software integration of the control and data planes. As an example of global optimization applied to SDS, consider storage systems where an individual storage system level tiering policy [5] is configured. A global tiering optimization policy across multiple storage systems would be able to rebalance the load by moving data to a more idle storage system, possibly passing along the original tiering information of that data to improve placement within the new system. As an example of increasing levels of software integration applied to SDS, consider the typical RAID (Redundant Array of Independent Disks) function: Initially, only a static configuration of Logical Unit Number (LUNs) with preconfigured RAID levels is presented by the hardware (storage system) to the software (running in the servers); then, software becomes capable of configuring LUNs with desired RAID levels through a programmatic interface to the hardware; finally, the RAID function is performed in software, eliminating the hardware availability restriction and enabling optimizations such as distributed RAID across nodes.

The following example illustrates the goals associated with SDS at a high level, contrasting the existing situation with the expected benefits of SDS. Currently, an application deployment starts by having the application designer state the expected storage capacity and performance requirements, followed by having the storage administrator define logical volumes for the required storage capacity and map them to the application. However, the application lifecycle is dynamic, and will require the storage administrator to manually adjust for various events: storage capacity needs to be increased or decreased; application performance degrades due to resource contention; performance requirements change (increase or decrease); data protection needs change; replication policies change; Recovery Point Objective (RPO) and Recovery Time Objective (RTO) of the data changes; backup and archive policy changes. In the future, applications are expected to specify storage requirements explicitly, including aspects related to performance, capacity, RPO/RTO, and replication. An orchestration component will automatically identify and configure the appropriate compute, network, and storage resources needed to satisfy the requirements. If the performance of an application is impacted, the orchestration component will automatically detect it and adjust resources to satisfy the requirements. If the requirements change, applications will indicate that to the orchestration component so resources are adjusted accordingly.

This example captures both the horizontal dimension of global optimization achieved across compute, network, and storage resources, as well as the vertical dimension of a programmatic API (application programming interface) to automatically configure and adapt resource requirements as changes are detected. It also shows on-demand configuration of storage infrastructure capabilities based on application/workload requirements. By abstracting infrastructure capabilities into generic storage capabilities independent of device- or vendor-specific capabilities, consumers of a storage service are decoupled from infrastructure details. Likewise, storage service providers gain flexibility as to which storage resources are used for fulfilling a given storage service request, characterized by capacity and required service class. Service providers automate the storage allocation process by defining a catalog of service classes, and specifying in configuration templates how storage within each class is allocated for the various types of storage resources available.

The key contribution of this paper is a novel SDS solution named IBM Open Platform for Storage, which embraces the open ecosystem based on OpenStack** with extensible and interoperable APIs. In addition, it enables seamless integration with enterprise storage management tools. Our solution provides a unified storage control plane that enables SDS functionalities and serves as an integral component of the software defined environment landscape.

The remainder of the paper is organized as follows. We first summarize the state-of-the-art SDS solutions and discuss their advantages and shortcomings. Next, our SDS solution, i.e., IBM Open Platform for Storage, is introduced, and detailed descriptions of SDS capabilities are provided. In addition, the orchestration among our SDS solution and other components in SDE is discussed. Finally, we use a case study of IBM Connections deployment in an SDE lab to illustrate the benefits of our SDS solution and conclude the paper.

State-of-the-art software defined storage solutions

This section discusses related work relevant to the subject of this paper. The emerging SDS solutions can be categorized into two groups based on their level of openness and the existence of associated ecosystems.

Software defined storage in enterprise solutions

For years, the storage industry has been facing challenges in managing heterogeneous storage devices which typically have their own management interfaces and protocols. Among the first solutions was the Storage Management Initiative Specification (SMI-S) [6] proposed by the Storage Networking Industry Association, which defined interoperable unified constructs to ease management tasks across heterogeneous storage devices. However, in order to achieve the objectives of SDS as presented in the previous section, additional enhancements are needed in the storage management layer to enable dynamic, agile, and highly automated solutions. In particular, the SMI-S defines interfaces at the data-plane layer, but does not address the SDS requirement of storage infrastructure capabilities to be represented in service-oriented, device-agnostic form, so that application requirements can be mapped to these capabilities.

As an example for an industry effort to close the gap between SMI-S and SDS, the IBM Virtual Storage Center (VSC) [7], with components of SAN (storage area network) volume controller (SVC) [8] for storage virtualization, Flash Copy Manager [9] for application-aware snapshot management, and the IBM storage resource management software product Tivoli Storage Productivity Center (TPC) [10], introduced a Storage Management API for Clouds (SMAC), which provides for a separation of concerns between storage service providers and storage service consumers. The SMAC API allows storage consumers to request new storage capacity by communicating the storage service requirements of this new capacity in abstract and service-oriented terms, without requiring them to have any knowledge about the resources in the storage infrastructure, such as device-specific capabilities. The entities surfaced by the SMAC API are (1) *Service Class*, which serves a dual purpose: for the provider, it represents storage management capabilities present in the storage infrastructure in abstract and device-independent terms; for the consumer, it captures the storage service requirements being requested for a given application; (2) *Capacity Pool*, which groups storage resources to satisfy new storage requests. These pools may be organized, for instance, along organization hierarchy, geography or by service classes the storage resources in the capacity pool support; and (3) *Delivery Unit*: a specific existing storage capacity, such as a storage volume or NAS share, along with its storage service requirements. A storage service consumer will request new delivery units, specifying the service class needed for the new delivery unit, and from which capacity pool it should be provisioned. TPC then determines the most appropriate storage resource it knows about from the specified capacity pool which fulfills the specified service class, in order to place the new delivery unit.

Further conceivable enhancements to TPC and the SMAC API include addressing the need for improved elasticity and flexibility. Also, a more comprehensive implementation of the various possible categories of storage service requirements, such as availability, security, and retention, is needed for a more complete establishment of an SDS control plane, which also serves as one of the motivations of our work as will be introduced shortly.

As of this writing, the specification of the SMAC API is not yet publically disclosed, but is used internally by other IBM offerings. An example offering making use of the SMAC API is the IBM SmartCloud* Storage Access [11] that implements a solution for building a private storage cloud, including abilities to monitor space consumption by tenant and enabling chargeback to them for the capacity they use. Other IBM products utilizing SMAC for automated, service-oriented infrastructure provisioning including storage are Tivoli Service Automation Manager [12] and IBM SmartCloud Orchestrator [13].

Other vendors have also been active in closing the gap between storage infrastructure management as enabled by SMI-S, and providing an SDS solution. Examples for these activities available in the market include EMC ViPR** [14], NetApp ONTAP** [15], Coraid EtherCloud Storage Manager** [16], among many others. In [17], an SDS architecture is proposed on a Windows**-based I/O stack to facilitate fine-grained I/O service differentiation. However, so far none of these provide the functional or device support coverage required for establishing a comprehensive SDS solution.

Software defined storage in the open source community

OpenStack is an open source cloud management project, which has seen significant adoption and vendor participation. OpenStack provides a platform for SDS and creates levels of abstraction between the storage and how it is consumed by applications. At this time, OpenStack includes two storage components: *Swift*, providing object storage to applications; and *Cinder*, providing block storage for VMs (virtual machines). Support for making file storage visible to VMs is on the roadmap of OpenStack, and key industry vendors, including IBM, are collaborating to provide this functionality.

OpenStack Swift is an object storage system, which manages and provides object storage to clients. The object storage is accessed via a REST (Representational state transfer) API, called Swift API, which is similar to Amazon S3 API or CDMI (Cloud Data Management Interface) [18]. Swift is architected to offer resilient and scalable storage, which automatically replicates data across available disks and nodes to provide scalability, availability and data protection. Swift is targeted to provide low cost storage as it can be run on storage rich commodity servers. Swift is also used by other OpenStack components. Swift can provide the VM image back-end repository for OpenStack image management and serve as a target for volume backups. Object storage is a very popular platform for new applications, especially those created and for the most part using resources provided by the Web due to the prevalent use of REST over HTTP. It provides the scalability and agility that file- and block-based storage is lacking because of the strict inherent legacy semantics embedded into them. Moreover, IBM Research has demonstrated advanced capabilities such as computational storage [19], metadata and search [20], and secure multi-tenancy for object storage [21].

OpenStack Cinder is the persistent storage management component in OpenStack. Cinder provides block-storage management, such as volume allocation and volume attachment to servers. A key feature of Cinder is a unified Cinder API to manage heterogeneous storage, and a set of pluggable backend drivers that interface with the storage systems. Today, Cinder manages high-end storage systems, such as IBM XIV* and SAN Volume Controllers, mid-range systems, like IBM Storwize* systems, distributed storage systems such as IBM GPFS* (General Parallel File System) [22] and even commodity storage using Linux** LVM (logical volume manager). Cinder includes a mechanism to report the capabilities and state of the storage system. Capabilities can include items such as media type, protocol, and compression support, while state can include available free space. Further, administrators can define “volume types” which define a named set of requirements. Users may then choose a volume type when creating a volume, providing requirements for allocating their storage. Cinder has a rudimentary “filter-scheduler” that compares the requirements supplied by the volume types with the capabilities provided by the storage system, and chooses a storage system that satisfies the requirements. OpenStack’s architecture allows for schedulers to be plugged in replacing the default scheduler, allowing 3rd party analytics tools to be utilized. OpenStack’s support for storage system capabilities and the ability to tag volumes by volume types is the first level of storage resource abstraction. This abstraction can be exploited by advanced management tools to provide SDS management. In the Havana release of OpenStack, Cinder supports volume migration between storage systems through volume migration features available in the storage system, or by leveraging volume migration support in KVM (Kernel-based Virtual Machine) [23].

OpenStack is an emerging platform with wide industry support, but is still lacking key features to address the complexity of enterprise applications, such as backup, disaster recovery, fabric management, advanced volume placement, and continuous storage optimization—challenges for which solutions are described in [24, 25]. Of the features listed above, initial solutions for backup and fabric management are emerging. IBM Tivoli Storage Manager (TSM), the IBM data protection product for open systems, has limited support for OpenStack starting in the Havana release. Fabric management is evolving with the introduction of availability zones in Cinder but still includes the assumption of any-to-any connectivity. In summary, OpenStack provides a viable platform for SDS but is still only an infrastructure-as-a-service solution as of today, which should be complemented with advanced solutions for workload management, service level management and information lifecycle management. In the next section, we will introduce the IBM Open Platform for Storage framework, which enjoys the flexibility and interoperability of the OpenStack ecosystem while providing enriched enterprise level storage management solutions by incorporating the salient features of the aforementioned VSC.

IBM Open Platform for software defined storage

The IBM Open Platform for Storage framework is one of the essential components in the IBM SDE architecture to provide SDS management functions. **Figure 1** illustrates a conceptual architecture of the overall SDE architecture. Various workloads are described using declarative workload abstraction methods to capture the application-specific requirements such as infrastructure architecture and business operational workflow. Another core component of the SDE is the resource abstraction layer which provides a unified interface for the provisioning, management, and monitoring of underlying resources in compute, networking, and storage domains. Therefore, the complexity of heterogeneous device management is transparent to users. The core SDE Unified Control Plane interprets the workload abstraction and manages the underlying resources to provide integrated services customized to the specific application requirements. In other words, it interprets the workload requirements, the abstraction of underlying resources, and orchestrates the SDC, SDN, and SDS components for agile and efficient management. Our proposed IBM Open Platform for Storage is the framework in SDE which enables SDS capabilities and interacts with counterparts of software defined compute and SDN. The framework provides a unified programmable control plane that allows Service-Level Objective (SLO)-oriented storage management on top of heterogeneous data planes. The framework is extensible and aligned with the OpenStack APIs for interoperability and consumption,

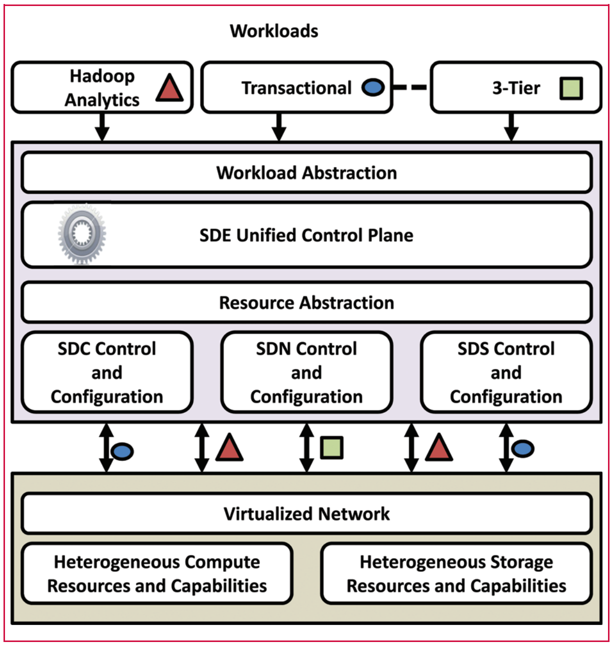


Figure 1

Architectural view of software defined environments. The ovals, triangles, and squares represent different types of workloads.

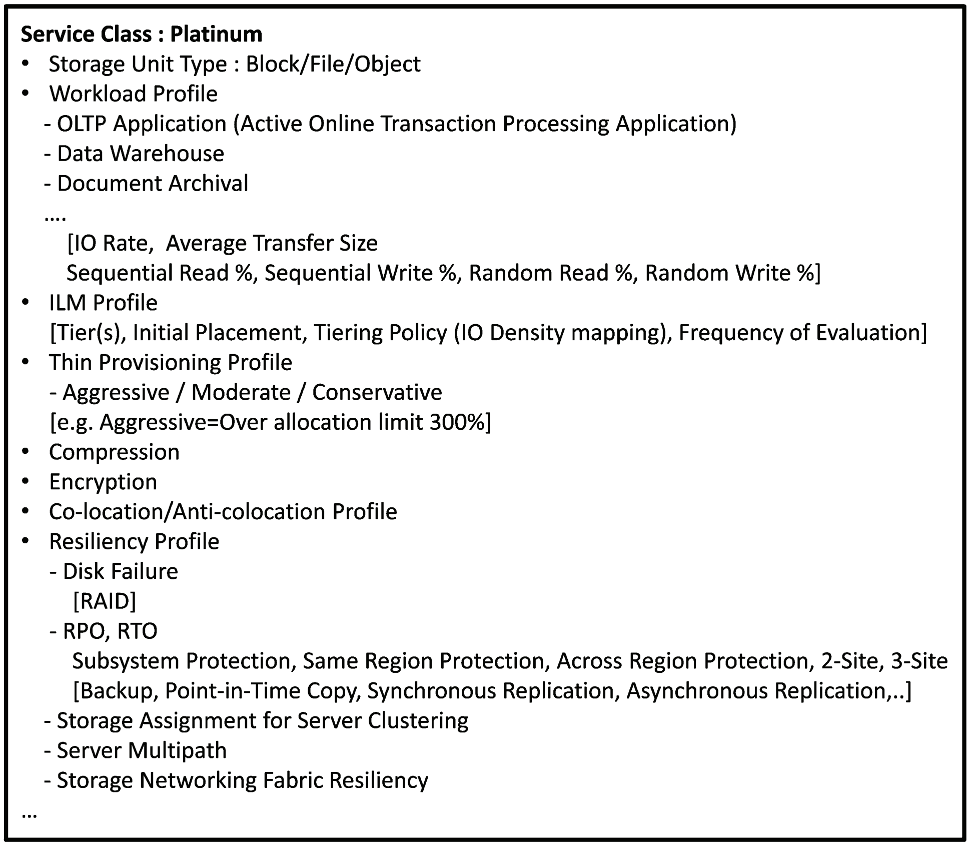
which is also the objective of the overall SDE architecture. In addition, our solution provides a pluggable interface to integrate with enterprise storage management products by implementing a Cinder filter scheduler. From a functional perspective, the framework building blocks include (1) workload abstraction, (2) resource abstraction, (3) workloads-resource mapping, and (4) continuous optimization. Next, we will provide detailed descriptions on each of the building blocks.

Workload abstraction

The rigid boundaries of compute, storage and networking in traditional IT environments impose significant challenges for efficient and agile application development and service deployment. In order to improve the portability and promptness of novel software and services delivery, declarative and expressive methods to capture the software and infrastructure requirements of the workload [26] are strongly desired where software patterns and infrastructure patterns can be tightly linked. In the open source community, TOSCA (Topology and Orchestration Specification for Cloud Applications) proposed by OASIS (Organization for the Advancement of Structured Information Standards) [27] and Linked Data format by OSLC (Open Service for Lifecycle Collaboration) [28] are popular methods to describe and manage the resources that applications require throughout their lifecycles. For example, a traditional three-tier web application may request a web server, a database server, an application server, and this software pattern will be captured in one of the declarative language formats, e.g., JSON (JavaScript** Object Notation) or XML (Extensible Markup Language). Orchestration engines such as IBM SmartCloud Orchestrator and OpenStack Heat will parse the specifications and orchestrate the deployment of resources on the underlying infrastructure accordingly. From a storage perspective, the framework creates extensions on both the workload descriptive tools and orchestration engines to expose sufficient and flexible storage semantics and primitives. For example, in the workload description, the application can specify the size of a storage volume, the desired service class, and its associated policy including, but not limited to, workload profile [e.g., I/O requirements of online transaction processing (OLTP) or batch processing], resiliency profile (e.g., Recovery Point Objective and Recovery Time Objective), among many others. Therefore, the framework allows the application developers and system administrators to explicitly specify their desired properties and features for underlying storage resources. Such user-specific storage requirements can also be adjusted throughout the application lifecycle as the workload changes, which significantly enhance agility and flexibility. **Figure 2** shows an example of the workload abstraction and its association with the resource abstractions. As shown in the example, the user can specify the type of storage requested, the workload profile (e.g., batch processing job or transactional workload), and desired storage features such as compression, encryption, tiering policies, among others.

Resource abstraction

As one of the key differentiating features of SDE, resource abstraction of heterogeneous resources is of paramount importance to enable unified infrastructure management and optimization. The IBM Open Platform for Storage supports a variety of underlying storage resources ranging from enterprise disk subsystems to commodity storage devices such as the GPFS GSS solution based on low cost storage disks. In addition, the framework is able to manage and aggregate disparate storage resources from Storage Area Network, NAS (Network-Attached Storage), or DAS (Direct Attached Storage) architectures and provides a unified storage resource abstraction layer which allows users to allocate storage in consumable units of a block, file, or object type. For example, the framework can create a file in the GPFS platform using low cost storage devices, expose the file as a block storage volume for virtual machine consumption, and use GPFS functions such as snapshot and file migration to manage the virtualized block device. The underlying management complexity is transparent to the end user and the storage resources utilization efficiency can be improved. Therefore, the framework provides a logical storage resource abstraction view which significantly reduces



Service Class : Platinum

- Storage Unit Type : Block/File/Object
- Workload Profile
  - OLTP Application (Active Online Transaction Processing Application)
  - Data Warehouse
  - Document Archival
  - ….
    [IO Rate, Average Transfer Size
    Sequential Read %, Sequential Write %, Random Read %, Random Write %]
- ILM Profile
  [Tier(s), Initial Placement, Tiering Policy (IO Density mapping), Frequency of Evaluation]
- Thin Provisioning Profile
  - Aggressive / Moderate / Conservative
  [e.g. Aggressive=Over allocation limit 300%]
- Compression
- Encryption
- Co-location/Anti-colocation Profile
- Resiliency Profile
  - Disk Failure
    [RAID]
  - RPO, RTO
    Subsystem Protection, Same Region Protection, Across Region Protection, 2-Site, 3-Site
    [Backup, Point-in-Time Copy, Synchronous Replication, Asynchronous Replication,..]
  - Storage Assignment for Server Clustering
  - Server Multipath
  - Storage Networking Fabric Resiliency

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Figure 2

Example of a service class and storage resource mapping.

the storage management complexity, achieves better storage resource utilization, and improves operational efficiency.

From a storage functionality perspective, the framework exposes two broad abstract categories of capabilities, i.e., (1) security and availability and (2) performance and optimization. In security and availability, storage capabilities such as authentication, auditing, encryption, data protection, high availability, among others are captured. The functions in performance and optimization include data striping, clustering, compression, de-duplication, and information lifecycle management (ILM, or tiering), which will be introduced in detail shortly.

It is worth noting that the way the framework invokes aforementioned functionalities varies according to the underlying storage infrastructure. For example, high-end enterprise storage subsystems have firmware-level advanced storage capabilities such as compression and de-duplication. In such scenarios, the framework uses these features by providing device-specific configurations using standardized or proprietary protocols. If the desired functionality is not available at the underlying storage devices, the framework invokes a software implementation to achieve the same functions such as compression and software-based RAID for data protection e.g. GPFS de-clustered RAID. From the end user's perspective, the implementation details are hidden and the platform is able to make optimal decisions based on business objectives and heterogeneous storage infrastructure to strike a balance between quality of service and cost.

Mapping to resources

The SDE Unified Control Plane obtains configuration information of the underlying infrastructure via resource abstraction. When a new request is received in a workload description format, the control plane will orchestrate among compute, networking, and storage for holistic resource provisioning. For storage resources, the control plane will extract the storage requirements in the workload description and pass the information to SDS for programmable workload to resource mapping. The storage resource mapping usually consists of three components, which will be introduced next.

Performance-aware storage placement

One of the key features enabled by the IBM Open Platform for Storage is the performance-aware storage placement capability. For each storage resource creation request, a "service class" needs to be specified, which captures the specific requirements for storage provisioning, e.g., RAID level and resiliency profile. Each service class represents a set of preconfigured storage configurations. The user can create new service classes, within the bounds of service class permutations supported by the service provider, which better characterize their specific workload. Note that the service class can be specified by workload abstraction tools using declarative TOSCA and OSLC formats. For example, a "Platinum" service class captures stringent storage requirements such as OLTP-High workload which requires low I/O latency with extensive random I/O accesses, and thus the storage volume created under this service class will be preferably placed on solid-state drive (SSD) instead of hard disk drive (HDD). In addition, if multiple storage pools are available to place the new storage volume, e.g., multiple SSD pools are available in the managed environment; the framework performs advanced storage performance analytics to decide which SSD pool should host the new volume. For example, when a new storage volume creation request is received with a "platinum" service class for OLTP-High workloads, the framework first analyzes the resource utilization conditions of all candidate SSD storage pools using historical data, and performs what-if analysis to predict the performance impact in terms of I/O load and latency by invoking the IntelliMagic/DiskMagic [29] whitebox model which can model the disk performance under various I/O activities. A simple strategy would be placing the new storage volume on the SSD which yields minimum performance impact, e.g., minimum response time changes. Other complementary performance-aware storage placement strategies, e.g., load balancing or minimum number of occupied storage devices, can be incorporated. It is also worth noting that the placement objective can also be configured per service class. Therefore, the coupling of service class and performance aware storage provisioning greatly enhances the flexibility and efficiency of storage provisioning where application-specific storage resource requirements can be specified, satisfied, and optimized.

Storage fabric management

Once the storage unit is created, the IBM Open Platform for Storage will establish the connection between the server and the storage volume. The framework provides a unified control plane for various storage networking techniques such as Fibre Channel, iSCSI (Internet Small Computer System Interface), InfiniBand**, and FCoE (Fibre Channel over Ethernet). The framework provides best practice-based zone management and fabric analytics to identify the best storage fabric configurations for servers and storage backends. For example, by analyzing the port utilization information on storage devices, the framework will intelligently provide load balancing for devices with multiple I/O ports to prevent over-utilization. Due to the combinatorial nature of the optimal fabric configuration problem, the framework employs an iterative hill-climbing algorithm to search the solution space and prune inefficient configurations until an optimal storage fabric configuration is identified.

Resiliency

Resiliency is of great importance for data protection and business continuity. The IBM Open Platform for Storage provides resiliency in the form of fabric resiliency and storage device level data protection. For fabric resiliency, the application can choose to have independent I/O paths from the compute server to the storage backends with no single point of failure. For storage device level data protection, the framework can allow the application to choose a replication strategy among several options such as point-in-time snapshot, synchronous mirroring, and asynchronous mirroring. Furthermore, the framework can provide application aware data protection by defining consistency groups to ensure resiliency. From the overall SDE viewpoint, the framework is an integral component providing end-to-end resiliency, which can obtain the compute domain information, e.g., server cluster setup for failover purpose, and then configure multi-path resiliency to guarantee that both the primary server and standby secondary servers can have reliable storage access to mitigate the impact of failures.

Continuous optimization

One example of continuous storage optimization provided by the framework is a concept known as storage information lifecycle management (ILM). The motivation is that the value of data is time-varying in its lifecycle. For example, the value of an email will decrease rapidly over time and it is more cost-effective to place archived email on low cost storage devices due to infrequent access, while the most frequently accessed data is placed on the high-end storage devices with low latency. The objective of storage ILM is to place the right data on the right storage tier at the right time. The placement of data on different storage resources based on I/O activities is also known as storage tiering. Note that while the data tier is categorized based on the historical I/O activities, the tier of storage devices are usually labeled by a manual process according to their performance and/or cost. Our framework allows applications to control storage ILM based on their unique needs. For example, each service class can specify the upper and lower bound of storage tier that will be used, and the automatic tiering policy can be specified in terms of I/O thresholds. Therefore, the IBM Open Platform for Storage provides granular control functions to explore the tradeoff between performance and cost for each application or workload. We will provide more examples of continuous storage optimization when describing an end-to-end scenario of SDE leveraging our framework capabilities.

SDE integration

Traditional data center IT solutions view compute, storage, and networking domains as separate management entities where different administration and management solutions are provided. However, due to the increasing demand for rapid and agile application service deployment, this traditional management paradigm significantly hinders the speed and efficiency of new IT service evolution. From a data center user's perspective, the perceived system performance experienced by applications depends on the integration of compute, networking, and storage. A holistic view of the data center with intelligent orchestration schemes will break the silo barriers of compute, network and storage, and significantly increase the quality of service and quality of user experience. In our SDE framework, the IBM Open Platform for Storage enables SDS functionalities and provides an integrated interface for orchestration with other components in SDE such as software defined compute and SDN. Our framework defines simple, yet rich programmable APIs (e.g., RESTful OSLC-compliant APIs) that allow joint optimization among various components in the SDE. In the following sections, we briefly discuss a few examples of the orchestration of SDE that can utilize the flexible interfaces the framework provides.

Storage-aware VM placement

Many VM placement algorithms have been proposed in the literature to solve the initial VM placement problem. Popular methods include CPU and memory aware placement, networking congestion aware placement, etc. In a data center with SAN storage architecture, a VM creation is usually associated with a vDisk (virtual disk) creation where the virtual disk is used to store the data for this VM and needs to be placed on the storage devices in the SAN. For I/O intensive applications, the storage access latency accounts for a significant portion of the total latency the application experiences. Therefore, the initial placement decision needs to consider where to place the VM on compute servers (i.e., CPU and memory resources) as well as the vDisk placement on the SAN, in a joint fashion. If the VM placement solution makes myopic decisions without obtaining sufficient knowledge and information from the storage domain, it is likely that the VM is placed on a server which has slow storage access, possibly due to a congested HBA/fabric switch on its I/O path. Therefore, the VM placement, especially for I/O intensive workloads, needs to consider all components along the I/O path comprising compute, networking, and storage, in order to make informed and efficient decisions. The framework provides flexible storage placement interfaces for the SDE Unified Control Plane, or simply the orchestrator, to make informed joint VM and vDisk placement decisions.

Integrated application resiliency

For many critical applications, resiliency is of great importance for business continuity. In order to mitigate the risk of unpredictable failures, redundant resources are provided for failover and fallback purposes. For example, a server cluster can be set up for an application where several servers are in standby mode and will replace primary servers in case of failures. From a storage perspective, data replication and high availability fabric configurations are important methods to handle unexpected device failures. The framework exposes such functionalities to allow the orchestrator to configure an end-to-end resiliency for the application across all domains in the SDE. It is worth noting that such decisions cannot be made without a holistic view. For example, it is possible that all servers in the server cluster share a same I/O path on the storage fabric. Therefore, while the resiliency in compute domain is assured, an integrated resiliency is missing. Our framework provides rich semantics to allow the orchestrator to achieve this comprehensive goal.

Service differentiation in SDE

In SDE, the resources are usually allocated according to the specific requirements of each application as well as its customizable service class. For example, a line of business application may enjoy better service in general compared to regular maintenance workloads. In our framework, each application can specify a service class which reflects the storage resource differentiation. The service class can be chosen from a set of predefined templates, e.g., OLTP-high or gold, or created according to the specific storage requirements. The framework provides sufficient flexibility which can facilitate differentiated services in the storage domain and can be orchestrated by the SDE control plane to provide a service differentiation across the data center.

Software defined storage in an SDE Lab and case studies

The proliferation and increased volatility of workloads and applications coupled with heterogeneous infrastructure requirements prohibits the manual deployment and tuning of applications. Automated and agile deployment is essential. In addition, continuous and optimal management of these workloads based on business policies is evident. To validate the constructs specified in this paper, and to facilitate the benchmarking of research results, IBM established an SDE lab consisting of scalable, heterogeneous infrastructure that includes PureFlex* servers [30], xSeries* and pSeries* servers interconnected with a high-speed switch fabric. The SDE lab divides the physical servers into Reusable Development Units, or RDUs, where each RDU comprises one or more physical servers according to the requirements of a tenant. As each RDU is allocated, the IP address and other RDU-specific information is defined in an XML file, which drives the Extreme Cloud Administration Toolkit (xCAT) [31] process that installs Ubuntu as the base operating system (OS). After the base OS is installed, control is passed to a Chef server [32], which uses community and customized recipes to install OpenStack and configure the network using additional parameters from the XML file. After the Chef recipes are complete, the RDU is usable and accessible via the OpenStack interface. Heterogeneous storage resources with a mix of enterprise-class, commodity, and direct attached storage are set up to provide the data plane. The control plane is enabled with a combination of OpenStack platform, our IBM Open Platform for Storage, and IBM Tivoli storage products.

Our demonstrations consist of multiple types of applications, e.g., Hadoop**/MapReduce analytics workloads, transactional OLTP workloads, three-tier web applications. To illustrate the application of SDE operations, we describe the "IBM Connections" workload [33], which is a three-tier web application. IBM Connections is a social software platform used internally by two hundred thousand IBM employees for business information exchange. Periodic brainstorming and knowledge exchange sessions such as the IBM InnovationJam* and the IBM Global Technology Outlook (GTO) drive very volatile workload requirements. Our SDE testbed emulates the scale, capabilities and operations of this environment under such volatile workload variations. From the SDS perspective, we demonstrate two major features of our platform: performance-aware storage placement and continuous storage analytics and optimization.

For performance-aware storage placement, the Connections application requires expertise in deploying and managing heterogeneous storage backends. In contrast, our platform can provide a unified storage control plane for various storage devices which are presented via resource abstraction. In addition, the Connections application consists of multiple components such as database, file sharing, archival, and each component has a different storage requirement. For example, the database component demands fast storage response time with high level of resiliency, whereas archival services may require low cost storage for cost efficiency and the response time is not a priority. In our framework, the Connections application can specify a workload description comprising "Database: OLTP-Platinum," "File Sharing: Gold," and "Archival: Silver," where the storage resource type is appended with its desired service class. The framework provides differentiated services for different service classes. OLTP-Platinum is always placed on tier-one storage first with fabric resiliency and metro-mirroring enabled, whereas the silver class will be placed on low cost storage. Therefore, our framework provides great flexibility and facilitates performance aware storage placement, differentiated via service classes.

For continuous storage analytics and optimizations, the framework can intelligently monitor and analyze the performance of each storage volume in order to meet the requirements of the Connections application. As introduced earlier, the Connections application will have fluctuating access patterns due to events such as IBM InnovationJam or Hackathon, during which the storage access will increase dramatically. Therefore, it is strongly recommended to place the storage volumes that are being accessed frequently on high end storage tiers with low response time and move them back when the access diminishes. Traditional storage management solutions need to manually plan the storage placement in advance to accommodate the fluctuation storage access pattern, and move storage volumes among various storage tiers following a predetermined process. In contrast, our framework provides intelligent ILM functionality that can monitor the I/O access of each storage volume, and automatically up-tier or down-tier the volume in line with the time-varying storage access patterns. The agility and automation enabled by the framework significantly reduces the management complexity. It is also worth noting that the automatic tiering policy is part of the storage requirements specified by workload description and captured by the service class. For example, it is likely that the database volume is critical in terms of overall quality of experience and thus favors a tiering policy that is aggressive in terms of up-tiering, compared to archival storage volumes. The framework provides fine-tuned customizability captured by service classes.

The scenarios discussed above focus on agile and flexible management of the underlying infrastructure resources. Integration with other development and operations (DevOps) and platform-as-a-service (PaaS) solutions are under investigation.

Conclusions and future work

In this paper, we investigated the emerging trend of SDS, which is an essential component of an SDE. The paradigm shift to SDE brings new challenges to storage provisioning and management. We provided an overview of the challenges involved as well as existing SDS solutions. As the focus of this paper, we presented the IBM Open Platform for Storage framework and described the design architecture and its unique features. In addition, we demonstrated the necessity of interlocking among storage, compute, and networking in software defined environments, where cross-silo joint optimizations can significantly boost the efficiency and performance of the data center environment.

The scenarios discussed in this paper focus on agile and flexible management of the underlying storage infrastructure. In the future, we are interested in exploring two research directions. First, we are investigating approaches to integrate our framework with other DevOps solutions. Second, we aim to align our solution with platform-as-a-service (PaaS) and software-as-a-service (SaaS) from a storage perspective.

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