Akademia Górniczo-Hutnicza
im. Stanisława Staszica w Krakowie

Wydział Elektrotechniki, Automatyki, Informatyki i Elektroniki

KATEDRA INFORMATYKI

PRACA MAGISTERSKA

KRZYSZTOF STYRC
Informatyka

ZARZĄDZANIE WIARYGODNOŚCIĄ I INTEGRALNOŚCIĄ DANYCH W SFEDEROWANYCH ZASOBACH CLOUD STORAGE

PROMOTOR:
dr inż. Marian Bubak

KONSULTACJA:
mgr inż. Piotr Nowakowski
ACC Cyfronet AGH, Kraków

Kraków 2013

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University of Science and Technology in Krakow

Faculty of Electrical Engineering, Automatics, Computer Science and Electronics

DEPARTMENT OF COMPUTER SCIENCE

MASTER OF SCIENCE THESIS

KRZYSZTOF STYRC
Computer Science

MANAGING DATA RELIABILITY AND INTEGRITY IN FEDERATED CLOUD STORAGE

SUPERVISOR:
Marian Bubak Ph.D

CONSULTANCY:
Piotr Nowakowski
ACC Cyfronet AGH, Kraków

Krakow 2013

Abstract

In the modern world of the 21st century the global volume of digital data is enormous and is supposed to continue growing exponentially. It is an engineering challenge to fullfill current and future data storage requirements. Nowadays, we observe a rapid shift from privately owned and maintained computer systems toward cloud storage with virtually unlimited storage capacity, high availability and built-in data replication. As we more and more rely on digital data, it is absolutely necessary to provide means of ensuring its availability and integrity. Although there exists well-established methods for providing data reliability such as error correcting codes, hash-based checksums, backups and replication, the cloud storage model poses new challenges. In this model, the data is stored remotely on external storage resources outside of user control. Although cloud storage providers guarantee service level agreement contracts, recent cloud failure and unavailability reports suggest that cloud storage is not free from dangers. It appears necessary to monitor the availability and integrity of data stored on cloud storage provider. However, network latency, bandwidth and data transfer fees makes hash-based validation of full content of large amounts of data inefficient and practically infeasible.

In the scope of this thesis we aim to address the problems and risks related to cloud data storage. As a result, we designed and implemented a tool that periodically monitors availability and integrity of data stored on cloud storage resources. The system was built on the basis of requirements originating from VPH-Share to enable scientists to tag datasets for transparent data monitoring and receive notifications in case of data integrity problems. We carefully examined the existing schemes of efficient data validation in the cloud. However, they clearly do not take into account current cloud storage limitations. The main contribution of this thesis is an efficient validation algorithm that with high probability can detect data availability and integrity errors while significantly reducing the amount of data transfer to 1 – 10% of the original file size. The application was successfully deployed and evaluated in the production environment of the VPH-Share project.

This work is organized in the following way. Chapter 1 provides an introduction and states the general objectives of this thesis. General methods of ensuring data availability and integrity, cloud storage overview and current approaches to data integrity in the cloud are presented in Chapter 2. In Chapter 3 and 4 we present the design and implementation of data reliability and integrity (DRI) tool in the scope of VPH-Share project. Validation and testing of DRI is presented in Chapter 5. Chapter 6 summarizes the work and discusses future work.

Acknowledgements

I would like to dedicate this thesis to my parents for their love and endless support in everything I do, as well as my beloved girlfriend Lidia, who was my continuous motivation on the way to finish this work successfully. I would like to thank my supervisor Dr Marian Bubak for sharing his experience and guidance throughout the process of writing this thesis. I would also like to express my appreciation to Piotr Nowakowski for his advisory in designing and implementation of the tool developed in scope of this work.

This thesis was realized partially in the framework of the following projects:

Virtual Physiological Human: Sharing for Healthcare (VPH-Share) - partially funded by the European Commission under the Information Communication Technologies Programme (contract number 269978).

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Abbreviations and Acronyms

ACL	Access Control List
AIR	Atmosphere Internal Registry
API	Application Programming Interface
AS	Atomic Service
CMDI	Cloud Data Management Interface
CRUD	Create Read Update Delete
DIP	Data Integrity Proof
DRI	Data Reliability and Integrity
ECC	Error Correcting Code
HAIL	High Availability and Integrity Layer
HMAC	Keyed-Hash Message Authentication Code
HTTP	HyperText Transfer Protocol
IaaS	Infrastructure as a Service
IETF	Internet Engineering Task Force
JAX-RS	Java API for RESTful Web Services
JAXB	Java Architecture for XML Binding
JSON	JavaScript Object Notation
JSR	Java Specification Request
JVM	Java Virtual Machine
LOBCDER	Large OBject Cloud Data storagE fedeRation
LSFR	Linear Feedback Shift Register
MAC	Message Authentication Code
PaaS	Platform as a Service
PDP	Provable Data Possession

POR	Proof of Retrievability
REST	REpresentational State Transfer
RFC	Request for Comments
RTT	Round Trip Time
S3	Simple Storage Service
SaaS	Software as a Service
SLA	Service Level Agreement
SNIA	Storage Networking Industry Association
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
UI	User Interface
URL	Uniform Resource Locator
VM	Virtual Machine
VPH	Virtual Physiological Human
WAR	Web Application Archive
WebDAV	Web Distributed Authoring and Versioning

1. Introduction

This chapter presents the overview and general objectives of this thesis. The first section outlines the background and the concept of assuring data reliability. Cloud storage availability and integrity challenges are introduced in the following section. Next, we present the origin of this work in the context of VPH-Share Cloud Platform. In the final section, the high-level objectives of this thesis are described.

1.1. Background and overview

In the modern world of the 21st century the data and its vast volume are ubiquitous. The total amount of global data stored to date is estimated as 4 zettabytes ($4 \times 10^{21} bytes$) in 2013, almost 50% more than in 2012 [33]. As long as computers spread to new domains and new computing paradigms – as internet of things and big data – become a reality, the trend of exponential growth of data volume will continue. The main sources of data are of various kind:

- **personal data** – generated by and associated with people such as images, videos, emails, documents etc, stored on privately held devices as laptops, smartphones or digital cameras as well as by website owners in big data centers,
- **business data** – generated by companies and corporations that enables them to run and maintain their daily business,
- **experimental data** – generated by all kind of sensor and experimental devices from weather stations, to particle accelerators, to space satellites and stored on academic resources and scientific data centers.

It is an engineering challenge to fullfill storage requirements for current data growth. Nowadays, we observe a rapid shift from privately owned and maintained computer systems toward virtualized computer infrastructures provided as a service, namely cloud computing. At least several commercial cloud infrastructure offerings provide access to virtualized computer systems at different level – Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). Low costs, high availability and scalability, decent performance degradation and seamless integration are often mentioned as major benefits by cloud adopters and evangelists.

Digitalization brought new opportunities and advantages to the business and communities. As a result, many of them became strictly tied to their data as a major asset and can no longer tolerate any data loss. Temporal data unavailability can also pose a problem in domains such as medical care and flight services. With the promise of scalable data storage, where everything can be stored or archived for

future needs, it is a burning issue to provide means of data loss prevention.

In general, the methods of data loss prevention can be divided into two groups:

(1) **corruption or loss detection** – that the data content is unavailable or no longer correct,

(2) **corruption or loss recovery** – that after data corruption detection we can recover its original properties of availability and integrity.

A number of methods exist and are in widespread use nowadays. Storage hardware solutions – CDs, hard disks, etc – utilize error correcting codes (ECC) to prevent small scale errors on read/write operations. Network protocols and software packages distribution use hash-based checksums to verify the integrity of the content. Data backups and replication are universal way of enabling recovery from data loss.

Ideally, from the user point of view, data storage solution should provide highly available and fault-tolerant access to the data and be free of data corruption and unavailability problems. However, it often appears that the above-mentioned criteria cannot be met in practice, especially when relying on single service provider. Cloud service providers protect their customers data with data replication to geographically distributed zones, strong securitiy policies and infrastructure monitoring. Even though, recently a number of cloud failures occured, questioning the reliability of cloud solutions [30] . Malicious and accidental data corruption threats also require attention.

The standard concept of checking data integrity is based on checksum verification. It consists of two major steps – initial setup and verification. The first step concerns with initial data deployment and computing checksum metadata of the content – a hash.In the verification step the integrity checksums of the data are once more computed and compared with the reference ones. In the scope of this thesis, we discuss the means of providing data reliability, by which we mean both:

(1) **availability** – that the data is available to the requesting entity,

(2) **integrity** – that the data remains untouched by malicious or undesired modifications.

Managing data availability and integrity of data in cloud storage environment is the subject of this thesis. As we mentioned above, to provide a solid way of assuring data reliability we must address both data corruption detection and recovery.

1.2. Cloud storage data reliability challenges

Over the last years, we observe a rapid shift from privately owned and maintained storage resources toward cloud storage solutions [29]. The cloud model of business become popular and adopted by many organizations. The main driving forces of cloud computing shift are low costs, high availability and scalability, decent performance degradation and seamless integration. While the emerging trend determines a significant step forward in storage technology and brings a lot of advantages as data replication, no administration costs, pay-as-you-use, SLA contracts – it can appear challenging for ensuring data reliability. Remotely available resources introduce network transfer rates and latency issues, while SLA contracts are mostly best-effort – cloud provider will not charge fees if service quality

has not been met. Additionally, recent cloud storage failures or security break reports shown that we cannot entrust our data to cloud providers entirely.

Classic checksum-based integrity verification methods are based on the whole content of data. It poses a challenge to efficiently verify the integrity of vast volumes of data stored on remote resources, where network transfer rates and latency comes into play. Additionally, cloud storage providers charge fees not only for storage space used, but also for storage transfer, especially outbound transfer. Consequently, cloud storage data reliability methods should take these limitations into consideration. It appears inevitable that cloud storage data integrity can be only provided with some level of probability and has to be based on a fraction of the file. A part of this thesis main objective is to select and implement a network-efficient method of ensuring data reliability.

1.3. VPH-Share Cloud Platform context

This thesis originates as a part of the VPH-Share project founded by European Commission which brings together twenty international partners from academia, industry and healthcare, led by University of Sheffield [13]. Its main goal is to build a collaborative computing environment and infrastructure where researchers from the domain of physiopathology of the human body will work together on developing new medical simulation software. The inspiring vision is to create a versatile environment for sharing of information – tools, models and data – to work efficiently towards building a complete model of the human body.

1.3.1. Basic architecture

The project has layered architecture divided into work packages distributed among consortium members (see figure 1.1). The design is based on cloud computing middleware – a hybrid of commercial and private resources on top of hardware layer. Data and Compute Cloud Platform is one of the main building blocks of the VPH-Share project. Its goal is to develop and integrate a consistent service-based cloud infrastructure that will enable VPH community to deploy basic components of VPH-Share application workflows (known as Atomic Services) on the available computing resources and then enact workflows using these services. Access to the services layer will be provided to system users through user interface(UI).

VPH-Share specifies three groups of users: application providers, domain scientists and system administrators [31]. Application providers are responsible for developing and installing scientific applications and software packages. Domain scientists are actual researchers of VPH community who will use and benefit from the platform. Finally, system administrators is a group of priviledged users who will manage platform's hardware resources and will administer and maintain it.

According to the platform's design, data will be stored on federated cloud storage resources – both commercial and private – and available via common access layer [31]. It is foreseen that stored data volumes will be significant, but predominantly of static nature – upon upload its content will remain untouched. Additional measures should ensure data availability and integrity.As a result, two of the key project's requirements regarding data storage and integrity are:

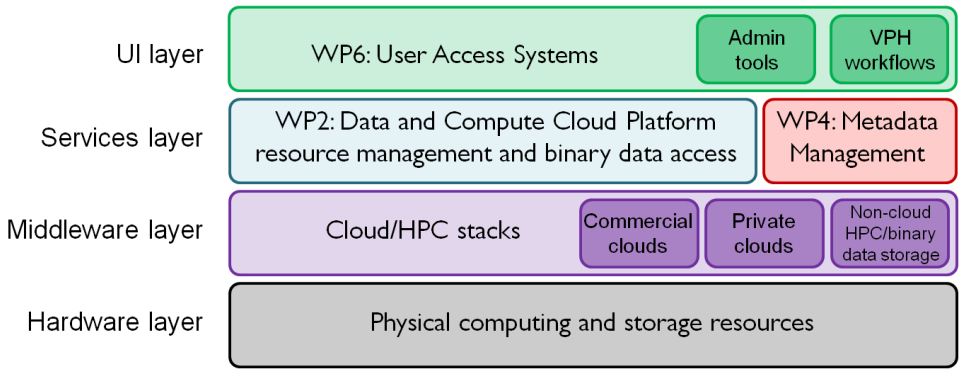


Figure 1.1: VPH-Share overview

The project aims to build a collaborative computing environment for researchers of human body to work on developing new medical simulation software. Its design has layered architecture centered around service-based Data and Compute Cloud Platform built on top of hybrid cloud middleware, both commercial and private. The VPH-Share users use the platform through common user interface layer [31]

(1) **access to large binary data in the cloud** – specified groups of users will be able to query for and store binary data uploaded or generated by workflows within the platform,

(2) **data reliability and integrity** – platform users will be able to tag datasets for automatic availability and integrity monitoring, set validation and replication policies, as well as receive notifications about data integrity violations.

VPH Cloud Platform puts strong empasis on data storage and availability and integrity assurance, as it is mostly static medical data of great importance. To fullfill this goal, VPH-Share bases on outsourcing data storage to multiple cloud storage providers – federated cloud storage. Data replication across cloud providers will build an abstraction layer on top of cloud services and will allow to use them interchangeably in case of cloud provider failure. Additionally, VPH-Share platform will periodically monitor the data availability and integrity of data and enable a possibility to restore corrupted entities from existing replicas. In case of irreparable corruption the owner should be notified about the problem.

1.3.2. Use cases and requirements

From the point of view of VPH-Share user a couple of crucial use cases regarding data availability and integrity can be identified:

- user tags a specific dataset (a set of files) for periodical data validation,
- user requests dataset validation,
- user requests dataset replication to the other cloud provider,
- user gets notified if data validation, periodical or on-request, discovered data unavailability or corruption.

The above use cases are provided by separate data reliability and integrity (DRI) component in service-based VPH-Share architecture. The formal functional and nonfunctional requirements of DRI are presented below.

Functional

Functional requirements are related to the core DRI capabilities that it is desired to ensure:

- **Periodic and on-request validation**: DRI has to periodically fetch datasets' metadata and check the availability and integrity of managed datasets. It also has to enable API interface for this operation to be invoked by the user on demand.
- **Data replication**: DRI has to enable API interface for data replication from one data source to the other.
- **User notification about integrity errors**: when DRI will discover data unavailability or corruption it should notify the owner about the identified problems.

Nonfunctional

Nonfunctional requirements are related to the quality of the core DRI capabilities:

- **Network-efficient validation mechanism**: As it was shown, naive whole file content validation seems infeasible in case of cloud storage of vast volumes of data. As a result, DRI should perform data validation efficiently from the perspective of network bandwidth, limiting the size of data that has to be downloaded to guarantee acceptable level of error detection.
- **Scalablility**: as it is foreseen that the amount of data stored in Cloud Platform resources will be significant, the DRI has to present the ability to scale with the size of data. It is suggested to be achieved by deploying many independent DRI replicas.
- **Configurability**: DRI has to provide API interface or UI portlet to configure its most important parameters regarding data validation.

1.4. Objectives of this work

As it was mentioned in the previous sections, there is a need to propose a method to manage data reliability and integrity in federated cloud storage, in particular within VPH-Share plaftorm environment. In this thesis, we present data reliability and integrity (DRI) component that monitors the availability and integrity of data. The high-level objective of this thesis is to design and implement such component that:

(1) efficiently and periodically monitors the integrity of the federated cloud storage,

(2) notifies the user about detected data corruption in advance of data retrieval,

(3) provides possibility to restore corrupted data from replicas in other cloud providers.

In the scope of this thesis, by efficient data validation we mean network efficiency. Our goal is to minimize network overhead incured against data source. While standard whole file content validation is practically infeasible when considering external storage and its vast volumes, we aim to propose an algorithm that only requires to fetch a fraction of file in order to detect data corruption on acceptable level of probability. Additionally, DRI should be scalable and configurable to flexibly adjust its network overhead.

Furthermore, we present a proof of concept implementation of DRI component as a part of service-based VPH-Share Cloud Platform environment, which significantly influences its design. DRI considers a concept of dataset – simply a set of files. Upon tagging dataset as managed DRI triggers integrity checksums computation and stores them in metadata registry. As long as dataset remains managed a periodical availability and integrity verification takes place. When data corruption is detected the user is notified about the errors via notification service and can restore the content from other replicas.

2. Data integrity

High-quality data availability and integrity property is a must-have requirement in many IT systems. A lot of enterprise and scientific effort has been put into development of tools and methods that support this capability. From cryptographic hash-based mechanisms that enable corruption discovery, to replication and error-correcting codes for data recovery, to security mechanisms preventing malicious data corruption. However, emerging trends in IT solutions, as cloud computing, put new challenges in this area. The following chapter presents the state of the art.

This chapter presents an introduction to a set of topics connected with data integrity in cloud storage. In the first section we present general methods and tools for ensuring data integrity which form fundamanetal building blocks for more advanced methods. Further, we describe cloud storage model, we focus on its origins and advantages, but also discuss limitations of its interface and SLA contracts. In the last section we dive into the subject of assuring data integrity in cloud storage and present some emerging methods: proofs of retrievability (PORs) and data integrity proofs (DIPs).

2.1. General methods and tools for ensuring data integrity

Providing a way to check the integrity of information transmitted over or stored in an unreliable medium is a prime necessity in the world of open computing and communications. The following section presents security building blocks that enable data integrity assurance. The cryptographic hash functions are core components of message authentication code algorithm to provide message integrity and authenticate the message creator. Error correcting codes are commonly deployed to be able to retrieve the original data after partial corruption.

2.1.1. Cryptographic hash functions

A cryptographic hash function is a hash algorithm that maps a message of arbitrary length to a fixed-length message digest (hash value). These algorithms enable determination of a message's integrity: any change to the message will, with high probability, result in a different message digest. This property appears very useful as a building block in various security constructions from generation and verification of digital signatures, to message authentication codes, to generation of random numbers.

A cryptographic hash function is expected to have the following properties [17]:

- **Collision resistance**: that it is computationally infeasible to find two different hash function inputs that have the same hash value. In other words, it is computationally infeasible to find x and x' for

which $hash(x) = hash(x')$.

- **Preimage resistance**: that given a randomly chosen hash value, $hash\_value$, it is computationally infeasible to find an x so that $hash(x) = hash\_value$. This property is also called one-way property.
- **Second preimage resistance**: that it is computationally infeasible to find a second input that has the same hash value as any other specified input. That is, given an input x, it is computationally infeasible to find a second input x' that is different from x, such that $hash(x) = hash(x')$.

Currently, the Secure Hash Standard (SHS) [18] specifies five approved hash algorithms: SHA-1, SHA-224, SHA-256, SHA-384 and SHA-512. Their strengths of the security properties discussed above, vary significantly. While one cryptographic hash function is suitable for one application, it might not be suitable for other. The general trend is that the longer the message digest (its hash), the stronger security guarantees, but also higher computational complexity.

Additionally, the algorithms differ in terms of the size of the blocks and words of data that are used during hashing or message digest sizes. They are presented in table 2.1.

Algorithm	Message Size (bits)	Block Size (bits)	Word Size (bits)	Message Digest Size (bits)
SHA-1	$< 2^{64}$	512	32	160
SHA-224	$< 2^{64}$	512	32	224
SHA-256	$< 2^{64}$	512	32	256
SHA-384	$< 2^{128}$	1024	64	384
SHA-512	$< 2^{128}$	1024	64	512

Table 2.1: Secure hash algorithm properties [18]

2.1.2. Error correcting codes

An error-correcting code (ECC) is an algorithm for expressing a sequence of numbers such that any errors which are introduced can be detected and corrected (up to certain level) based on the remaining numbers. All error correcting codes are based on the same basic principle: redundancy is added to information in order to correct any errors that may occur in the process of storage or transmission. In practice, the redundant symbols are appended to the information symbols to obtain a coded sequence (codeword).

ECC can be divided into two classes:

- **block codes**: that work on fixed-size blocks of predetermined size,
- **convolutional codes**: that work on bit streams of arbitrary length.

Among classical block codes the most popular are Reed-Solomon codes which are in widespread use on the CDs, DVDs and hard disk drives. Hamming codes are commonly used to prevent NAND flash memories errors. On the other hand, convolutional codes are widely used in reliable data transfer such as digital video, radio, mobile and satellite communication. Both block and convolutional codes are often implemented in concatenation.

Apart from embedding ECC in the hardware solutions, they are also being applied in software constructions to recover from eventual data corruption.

2.1.3. Message authentication codes

A message authentication code (MAC) is an authentication tag (also called a checksum) derived by applying an authentication scheme, together with a secret key, to a message [14]. The purpose of a MAC is to authenticate both the source of a message and its integrity without the use of any additional mechanisms.

MACs based on cryptographic hash functions are known as HMACs. They have two functionally distinct parameters: a message input and a secret key known only to the message originator and intended receivers.

An HMAC function is used by the message sender to produce a value (the MAC) that is formed by condensing the secret key and the message input. The MAC is typically sent to the message receiver along with the message. The receiver computes the MAC on the received message using the same key and HMAC function as were used by the sender, and compares the result computed with the received MAC. If the two values match, the message has been correctly received, and the receiver is assured that the sender is a member of the community of users that share the key [14].

To compute a MAC over the data $text$ using the HMAC function with key K, the following operation is performed [14]:

$$MAC(text) = HMAC(K, text) = H(((K_0 \oplus opad)||H((K_0 \oplus ipad)||text))) \tag{2.1}$$

where:

- K_0 – the key K after any necessary pre-processing to form a B byte key,
- $ipad$ – inner pad, the byte $0x36$ repeated B times,
- $opad$ – outer pad, the byte $0x5c$ repeated B times,
- B – block size (in bytes) of the input to the H hash function,
- H – an approved hash function.

The Internet Engineering Task Force (IETF) published a RFC document to describe HMAC [40].

Apart from HMAC, a couple of other MACs have been proposed. Stinson [50] presented an unconditionally secure MAC based on encryption with a one-time pad. The cipher text of the message authenticates itself as nobody else has access to the one-time pad. Lai et al. [43] proposed a MAC based on stream ciphers. In their algorithm, a provably secure stream cipher is used to split a message into two substreams and each substream is fed into a linear feedback shift register (LFSR); the checksum is the final state of the two LFSRs.

2.2. Cloud storage model

Cloud computing is an emerging IT trend toward loosely coupled networking of computing resources. Its core feature is to move computing and data away from desktop and portable PCs to large data centers

and provide it as a service. The popularity of this paradigm develops as it reduces IT expenses and provide agile IT services to both, organisations and individuals. Additionally, users are released from the burden of frequent hardware updates and costly maintenance, while paying for cloud services on consumption basis.

While cloud computing represents the full spectrum of computing resources, this work focuses on cloud storage services for archival and backup data. As it will be shown, this technology, apart from its advantages, introduces many problems, especially for ensuring data availability and integrity which may appear as untrustworthy.

2.2.1. General features

Cloud storage is a model of broadband network access to virtualized pool of storage resources on demand. In the spirit of cloud computing paradigm, it is mostly provided via REST/SOAP web service interface, however, other standard protocols are used. Despite incompatibilities among various cloud storage providers, as cloud computing gets more mature technology, their interfaces begin to standardize. Storage Networking Industry Association (SNIA) works toward developing a reference Cloud Data Management Interface (CMDI).

While different cloud storage solutions vary significantly, the following common properties can be derived:

- storage space is made up of many distributed resources, but still acts as one, virtualized layer,
- high fault-tolerance through redundancy and distribution of data,
- high data durability via object versioning,
- predominantly eventual consistency with regard to data replicas.

Typically, public cloud providers expose storage space as object data store, where data is organized into containers (or buckets). Each container consists of data objects (files) on which standard create, read, update, delete (CRUD) operations may be performed. Additional metadata is appended to containers and data objects such as name, size, creation/modification date or hash checksum.

Amazon Simple Storage Service (S3) [1], Rackspace Cloud Files [11] and Google Cloud Storage [5] are the most popular representatives of the illustrated cloud storage model. Despite the increasing popularity of public cloud storage providers, hybrid and private cloud solutions do exist, Openstack Swift [9] and Eucalyptus Cloud [4] to name just a few.

2.2.2. Interface and API

Current cloud storage systems mostly provide REST/SOAP web service interface to access the resources, in the spirit of Service Oriented Architecture (SOA) paradigm. While this thesis focuses on this method of access and its consequences, other providers expose different types of interface [36].

Despite the fact that web service interfaces enable loose coupling and technology interoperability, they require integration code with an application. Many multi-cloud libraries were created to enable interoperability across similar cloud services on a higher level of abstraction [42]. Their goal is to establish basic and uniform cloud storage access layer at the API level [2, 7].

Typically, cloud storage interfaces provide API to query, access and manage stored data, which can be divided into the following groups:

- **Operations for authentication**: to secure the access to cloud storage data (mostly via token-based authentication),
- **Operations on the account**: to operate on account metadata such as managing existing containers and additional provider-specific data services,
- **Operations on the container**: to manage container policy, versioning, ACLs, lifecycle and location,
- **Operations on the data objects**: to enable CRUD operations.

There exists a growing trend to adjust provider-specific interfaces with the SNIA reference model [1, 9, 11].

2.2.3. Service Level Agreement

To provide high quality of service, cloud storage providers widely guarantee Service Level Agreement (SLA) contracts. These are mostly related to service availability during the billing cycle. The service downtime is considered as cloud network error or response errors to a valid user requests. Currently, most of the providers guarantee the availability level of 99.9% of the time.

However, if the provider will fail to provide a guaranteed level of service, the appriopriate percentage of the credit is returned to the client. In this sense, cloud storage should be still treated as best-effort. IT systems that demand uninterrupted operation simply cannot entirely rely on it.

Moreover, eventual consistency model is inherently embedded into the overwhelming majority of cloud storage architectures, which places new problems to the solutions, where strict data consistency is a crucial requirement [23, 42]. Besides eventual consistency, SLA contracts still only address the service availability, while omitting data integrity or retrievability speed issues. Even though, cloud storage service with described limitations still fit to the vast number of market applications.

Customers who require a higher data availability and integrity guarantees, still need to seek for hybrid solutions and develop sophisticated layers on top of existing infrastructure to meet their demands.

2.2.4. Constraints and limitations

Cloud storage architecture presented in previous section exhibit many advantages to potential users. Nevertheless, it also introduces a couple of drawbacks for demanding solutions.

The most striking consequence of cloud storage, is that data is stored remotely on provider's resources and user has very limited possibilities to monitor or check its data through abstract access layer. Even small security vulnerability may compromise the data of all users in public cloud model.

As it was shown in previous subsection, cloud SLA contracts still lack strong availability and integrity guarantees, rather than cost-return policy. Even though cloud storage is perceived as superb technology, a couple of serious downtimes have been reported in the last years. Amazon S3 users experienced several unavailability and data corruption periods [12,39], while Google Gmail lost data of thousands of accounts [16] and Google Docs enabled unauthorized access to the stored documents [15]. The statistics and analysis of downtimes of current cloud solutions is presented in-depth in [30].

Cloud storage REST/SOAP interfaces are flexible and rich in capabilities, but when accessed remotely outside of cloud compute resources, they suffer from network latency for each HTTP request. Downloading a fragment of a file pose another challenge. It is mostly achieved by setting HTTP Range parameter to the desired value. However, only single range value is permitted. It is particularly problematic for data integrity monitoring protocols (presented in the next section) as they request a lot of small file's blocks, and for each block a separate HTTP request has to be sent, which means increased network overhead.

Moreover, cloud storage solutions lack user's code execution capability over stored data. The data has to be downloaded in order to perform computation. It makes present data integrity monitoring protocols impractical and inefficient, because they assume computation capability on the prover's side.

2.3. Approaches to data integrity in cloud storage

One of the fundamental goals of cryptography is data integrity protection. Primitives such as digital signatures and message-authentication codes (MACs), described in section 2.1, were created to allow an entity in possession of a file F to verify that it has not been tampered with. The simplest way is to use keyed hash function $h_k(F)$ to compute and store a hash value along with secret, random key k prior to archiving a file. To verify that the prover (remote server, cloud provider) possess F, the verifier releases key k and asks the prover to compute and return $h_k(F)$. By using multiple keys with their corresponding hash values, the verifier can perform multiple, independent checks. However, this approach introduces high resource overhead. It requires the verifier to store large number of hash values and the prover to read the entire file for every proof.

A more challenging problem is to enable verification of the integrity of F without knowledge of the entire file's contents. It was firstly described in general view by Blum et al. [25], who presented efficient methods for checking the correctness of program's memory. Following works concerned dynamic memory-checking in a range of settings. For instance, Clarke et al. [28] consider the case of checking the integrity of operations performed on an arbitrarily-large amount of untrusted data, when using only a small fixed-sized trusted state. Their construction employ an adaptive Merkle hash-tree over the contents of this memory. However, Naor and Rothblum showed that online memory checking may be prohibitively expensive for many applications [45]. This implies that applications requiring memory checking should make cryptographic assumptions, or use an offline version of the problem.

Unauthorized modifications to portions of files can be detected by cryptographic integrity assurance upon their retrieval. But in its basic form it does not enable such detection capability prior to the

retrieval, what many other schemes aim to provide.

One of the mostly developed model of ensuring integrity of remotely stored data is the proofs of retrievability (POR). The first formal description of POR protocol was proposed by Juels and Kaliski [37]. In their scheme, the client applies error-correcting code and spot-checking to ensure both possession and retrievability of files. Shaham et al. [47] achieve POR scheme with full proofs of security and lower communication overhead. Bowers et al. [26] simplify and improve the framework and achieve lower storage overhead as well as higher error tolerance. Later on, they extend it to distributed systems [27]. However, all these schemes are focusing on static data. Before outsourcing the data file F a preprocessing steps are applied. Every change to the contents of F require re-processing, which introduces significant computation and communication complexity. Stefanov et al. [49] propose an authenticated file-system for outsourcing enterprise data to the untrusted cloud service providers with the first efficient dynamic POR.

Atenise et al. [20] presented the provable data possession (PDP) model in order to verify if an untrusted server stores a client's data without file retrieval. Key components of their scheme are public key based homomorphic verifiable tags. In the subsequent work, Atenise et al. [21] described a PDP scheme that uses only symmetric key cryptography. As a result, they achieved lower performance overhead.

A couple of practical implementations for remote integrity assurance have been developed. Bowers et al. [27] designed HAIL (High Availability and Integrity Layer) which takes advantage of data distribution over a set of servers to achieve efficient POR-like scheme. Shraer et al. [48] created Venus, a scheme that guarantees integrity and consistency for a group of clients accessing a remote storage provider. Venus ensures that each data object read by any client has previously been written by some client. Additionally, it protects against retrieving older version of the object. Bessani et al. [24] implemented DEPSKY, a system that improves the availability, integrity and confidentiality of information stored in the cloud through encryption, encoding, and replication of data on diverse clouds that form cloud-of-clouds.

In the following subsections we examine exhaustively a couple of schemes mentioned above. We present their architecture, advantages and limitations.

2.3.1. Proofs of retrievability

In a POR [26,37] protocol, a file is encoded by a client before deploying it on cloud storage for archiving. Then, it employs bandwidth-efficient challenge-response scheme to probabilistically guarantee that a file is available at remote storage provider. Most of POR protocols proposed to date, use the technique of spot-checking in the challenge-response protocol to detect data corruption. In each challenge, a subset of file blocks is verified, and the results of a computation over these blocks is returned to the client. The returned results are checked using the original checksums embedded into the file at encoding time.

The primary POR-like protocol we consider in detail, was proposed by Juels and Kaliski [37] – a MAC-based POR scheme. In this approach, they firstly preprocess the file F by applying error-correcting codes and MAC checksums in the following steps:

(1) **Error correction**: the file is divided into b blocks of the same length and apply an (n, k, d)-error correcting code, which expands each chunk of size k into size n and is able to recover from up to $d - 1$ errors. The resulting file is denoted as F'.

(2) **Encryption**: the file with appended ECCs is encrypted.

(3) **MAC computation**: a m number of blocks are selected in F'', their MACs computed and appended to the file.

(4) **Permutation**: of file blocks to secure appended MACs against corruption.

The graphical presentation of the process is depicted in figure 2.1.

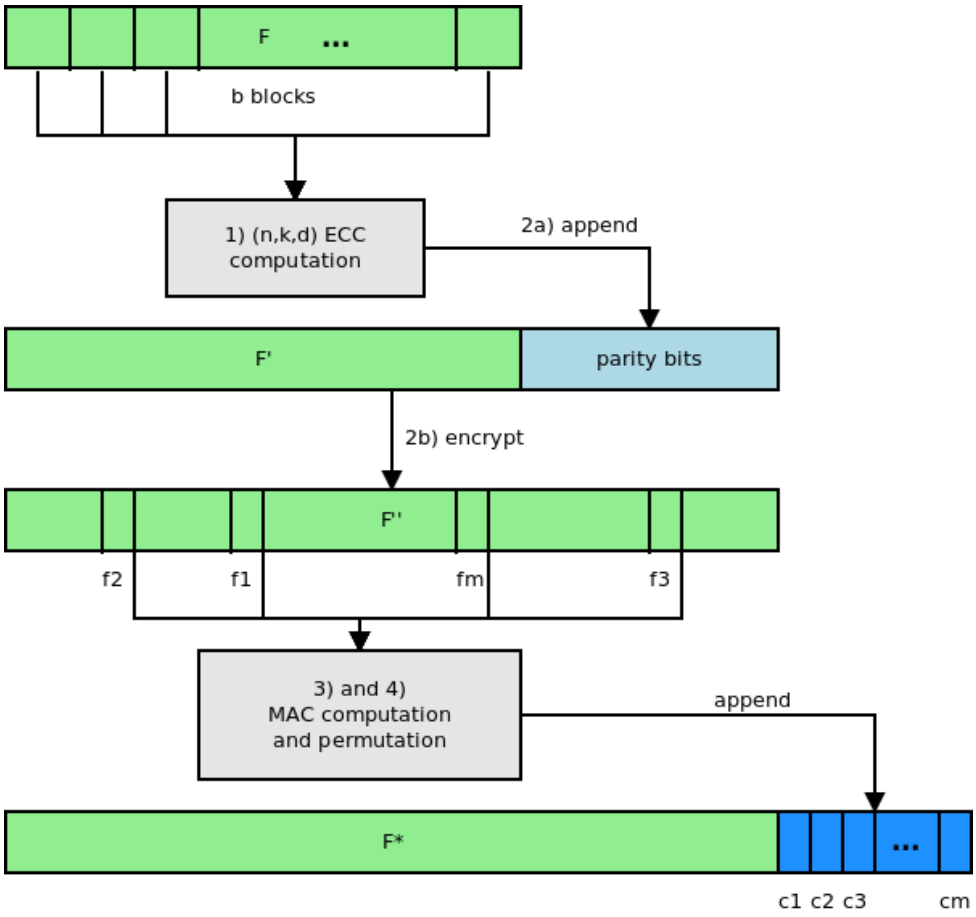


Figure 2.1: Schematic presents POR based file encoding. Firstly (1), the file is divided into b blocks and error correcting codes are applied to each of the block. Then (2), the parity bits are appended and the resulting file is encrypted. Finally (3,4), m blocks of the encrypted file are selected, their MACs computed and appended to the file in permuted sequence. The resulting file is stored in archive [37].

In the same paper [37], Juels and Kaliski proposed a sentinel-based POR scheme. Similarily to the MAC-based approach it utilizes ECCs, but rather than chosing MAC blocks it embeds sentinels in random positions in F, sentinels being randomly constructed values. It is important that sentinels shall be indistinguishable from the encrypted file contents. The scheme consists of the following steps:

(1) **Error correction**: the file is divided into b blocks of the same length and apply an (n, k, d)-error correcting code, which expands each chunk of size k into size n and is able to recover from up to $d - 1$ errors. The resulting file is denoted as F'.

(2) **Encryption**: the file with appended ECCs is encrypted.

(3) **Sentinel creation**: the randomly constructed sentinels are embedded in random positions in F'

(4) **Permutation**: which randomizes sentinel positions.

In both approaches, if the prover has modified or deleted a substantial e-portion of F, then with high probability, also change roughly an e-fraction of MAC-blocks or sentinels, respectively. It is therefore unlikely to respond correctly to the verifier. Upon file retrieval, the user verifies file's checksum. If it is not valid, then it starts file recovery based on stored ECCs.

Of course, application of an error-correcting (or erasure) code and insertion of sentinels enlarges F^* beyond the original size of the file F. The expansion induced by both POR protocols, however, can be restricted to a modest percentage of the size of F. Importantly, the communication and computational costs of the protocols are low.

The obvious advantage of the presented schemes is that they can be parameterized.

Subsequent POR works [27, 48, 49] introduced further optimizations to the solution described. Bowers et al. [27] propose to distribute data in RAID-like way and ensure file availability against a strong, mobile adversary. Stefanov et al. [49] go beyond basic data integrity verification and propose a solution to achieve two stronger properties: file freshness and retrievability. Shraer et al. [48] presented Venus, a practical service that guarantees integrity and consistency, while having insignificant overhead.

However, POR-like schemes are not free from drawbacks. The primary limitation is that preprocessing phase introduces non-negligible computational overhead. Moreover, it requires storage of file F in modified form. What is even more problematic, it assumes that storage service provides user's code execution capability, which is not true for current cloud storages (see section 2.2). For this reason, practical POR-like implementation would require moving prover logic for computing challenge-response queries to the verifier. As a consequence, each access to the portion of a file (MAC block or sentinel) would require separate HTTP request. As many such accesses are performed per each file, it would be impractical (except for large files, for which hundreds of short HTTP requests would be faster than downloading the entire file).

2.3.2. Data integrity proofs

Data integrity proof (DIP) [41] is a protocol, which just like POR, aims to assure that the remote archive poses the data. Unlike POR schemes, it does not involve any modifications to the stored file. The client before storing data file F, preprocesses it to create suitable metadata, which is used in the later stage of data integrity verification. The preprocessing stage consists of the following steps:

- **Generation of metadata**: the file F in divided into n blocks that each are m bits length. Then, for each data block, a set of k out of m bits are selected. The value of k is in the choice of the verifier and is a secret known only to him. Therefore, we get $n * k$ bits in total.

- **Encrypting the metadata**: each of the metadata from the data blocks, is encrypted by using a suitable algorithm and concatenated.
- **Appending the metadata**: all the metadata are appended to the file F, however, they can be also stored in the verifier.

The graphical presentation of the process is depicted in figure 2.2.

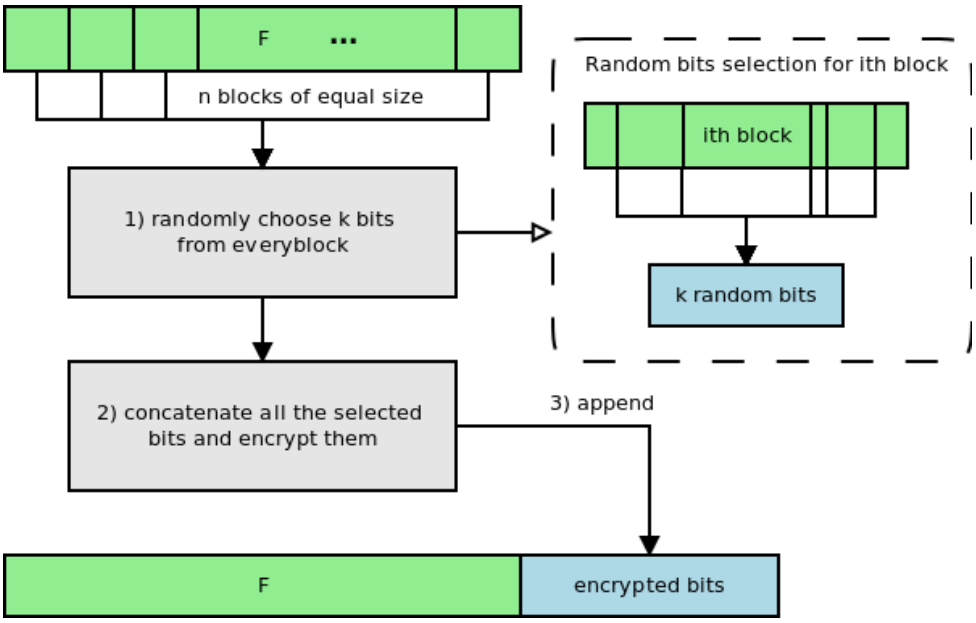


Figure 2.2: Schematic presents DIP based file encoding. Firstly (1), the file is divided into n blocks of equal size and k randomly chosen bits are selected out of each block. Then (2), concatenated bits from all of the blocks are encrypted and appended to the file F [41].

To verify F integrity, the verifier utilizes challenge-response mechanism. In each challenge, it verifies a single block i specifing the positions of the k selected bits and retrieves encrypted metadata for this block to compare the values. Any mismatch between the two would mean a loss of the integrity of the clients data at the cloud storage.

While DIP scheme seems trivial, it eliminates a couple of disadvantages of the POR approach. Firstly, data integrity assurance does not require any modifications to the stored file, but also prevents the data recovery capability by ECC. It also exhibits negligible computational overhead. However, it still either assumes user's code execution capability by cloud provider or requires large number of accesses to non-continuous data fragments. Such data acceses are performed in separate HTTP requests in the current cloud storages (see section 2.2), which is practically infeasible.

2.4. Summary

In this chapter an important topics regarding data integrity and cloud storage were presented. General methods and tools for ensuring data integrity such as cryptographic hash functions, error correcting codes and message authentication codes were discussed. They form a set of fundamental building blocks and patterns used in more advanced methods. Its understanding is crucial in further discussion on data

integrity throughout this thesis. Further, the overview of cloud storage model was presented. We focused on describing its origins in connection with advantages which it brings in numerous applications. The discussion also includes the high-level description of cloud storage interface and SLA contracts. We also stress the contraints and limitations of moving the data to the cloud. Shortly, recent cloud providers failure reports and the best-effort SLA contracts question the applicability of cloud storage in areas such as medical care and flight services. In the last section, we extensively discuss current approaches to data integrity in the cloud. We mainly focused on two developing schemes: proofs of retrievability (PORs) and data integrity proofs (DIPs), but also mention other solutions and improvements.

3. Data reliability and integrity service

This chapter presents the architecture of Data Reliability and Integrity (DRI) service. It starts by describing the environment of VPH-Share Cloud Platform which specifies requirements under which DRI operates. Then it defines its design and interfaces with other parts of the system. At the end, the core validation heuristic algorithm is presented.

3.1. Data and Compute Cloud Platform context

VPH-Share Data and Compute Cloud Platform project aims to design, implement, deploy and maintain cloud storage and compute platform for application deployment and execution. The tools and end-user services within the project will enable researchers and medical practitioners to create and use their domain-specific workflows on top of the Cloud and high-performance computing infrastructure. In order to fulfill this goal, Cloud Platform will be delivered as consistent service-based system that enables end users to deploy the basic components of the VPH-Share application workflows (known as Atomic Services) on the available computing resources and then enact workflows using these services.

3.1.1. VPH-Share groups of users

VPH-Share project identifies three specific groups of users [31]:

(1) **Application providers** – people responsible for developing and installing scientific applications and software packages, typically IT experts who collaborate with domain scientists and translate their requirements into executable software.

(2) **Domain scientists** – actual researchers of the VPH community who stand to benefit from access to scientific software packages provided by the platform. They will require the ability to access the applications in a secure and convenient manner via graphical interfaces provided on top of Cloud Platform.

(3) **System administrators** – priviledged users with ability to manipulate and assign the available hardware resources to the project and define security/access policies for other user groups. They will also make sure that the platform remains operational by taking advantage of notification mechanisms built into the system.

3.1.2. Cloud platform architecture overview

The general overview of Cloud Platform architecture with interactions to other parts of the VPH-Share is illustrated in figure 3.1. Master UI (web portal) enables coarse-grained invocations of the underlying

core services to the specified groups of end-users described in section 3.1.1. The Cloud Platform itself will be deployed on available cloud and physical resources.

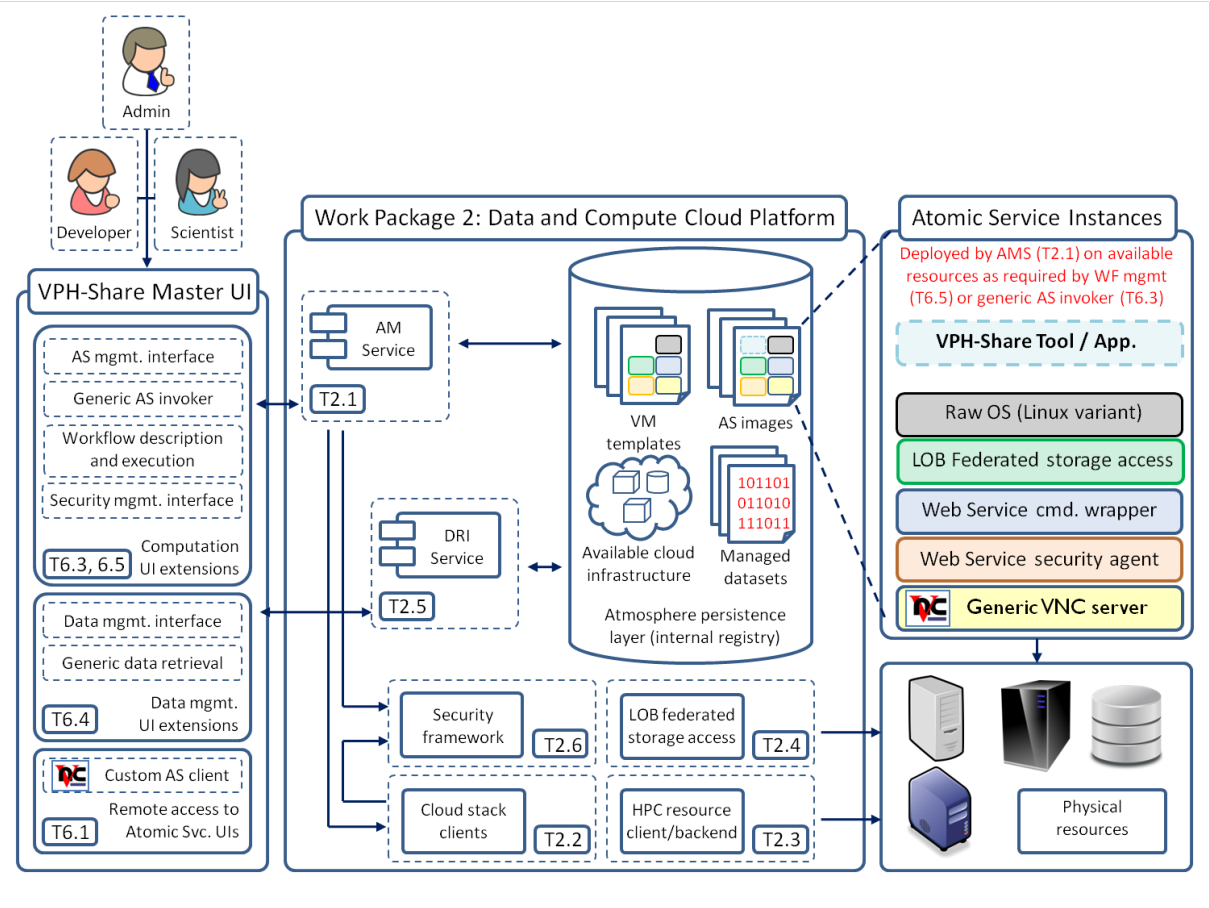


Figure 3.1: VPH-Share Platform architecture. Specified groups of users are provided with functionalities of Cloud Platform through Master user interface (UI) which enables coarse-grained invocations of the underlying core services. Data and Compute Cloud Platform consists of loosly-coupled services responsible for exposing different platform functionalities such as federated storage access (T2.4), data integrity monitoring (2.5) etc. Services are deployed as Atomic Service instances (simply a VM with add-ons). The platform is built on top of cloud computing resources [31].

Cloud Platform interally consists of many loosly-coupled components deployed as Atomic Service Instances (see section 3.1.5). Data storage is an essential functionality of the Platform. It is achieved by federated cloud storage which makes use of both, cloud and other storage resources with redundancy and is accessible through common data layer – LOBCDER service. Atmosphere Internal Registry (AIR) serves as centralised metadata storage component which enables integration between loose-coupled services and is presented in subsection 3.1.3.

In VPH-Share project a strong emphasis is placed on providing data integrity, availability and retrievability (that it can be retrieved at minimal specified speed). To fulfill this requirement, a Data Reliability and Integrity (DRI) service was designed, implemented and deployed as one of the core Cloud Platform's services – which is a primary topic of this thesis.

3.1.3. Atmosphere Internal Registry

The Atmosphere Internal Registry (hereafter also referred to as the Atmosphere Registry, the AIR component or simply the Registry) is a core element of the Cloud Platform, delivering persistence capabilities. Its components and interactions are depicted in figure 3.2. The main function of AIR is to provide a technical means and an API layer for other components of the Cloud Platform to store and retrieve their crucial metadata. Having a logically centralised (though physically dispersed, if needed to meet high availability requirements) metadata storage component is beneficial for the platform, as multiple elements may use it not only to preserve their "memory", but also to persistently exchange data. This is facilitated through the well-known database sharing model where the data storage layer serves as a means of communication between autonomous components, making the Atmosphere Internal Registry an important element of the platform.

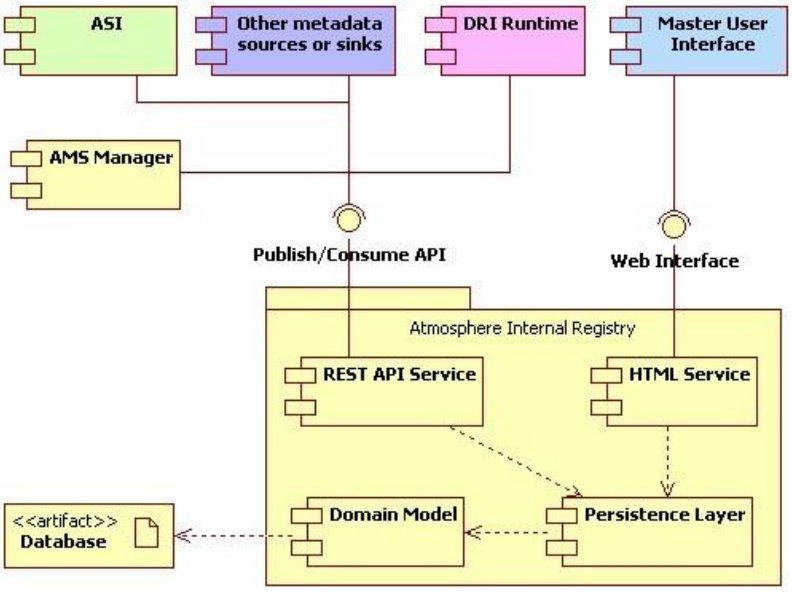


Figure 3.2: The overview of Atmosphere Internal Registry (AIR) component. Many VPH-Share core components store and access various metadata in AIR. It provides REST API interface for these components, as well as web-based html service to enable VPH-Share users to browse the metadata via Master UI [31].

From DRI perspective, AIR will store necessary metadata:

- **datasets metadata** and files they contain,
- **integrity checksums** for data validation,
- **service configuration**.

Such design enables us to implement DRI as stateless service.

3.1.4. Federated cloud storage

Data storage is an essential part of VPH-Share Cloud Platform. The increasing popularity of cloud storage services due to high quality-cost ratio is leading more organisations to migrate and/or adapt their IT infrastructure to operate completely or partially in the cloud. However, as mentioned in section 2.3,

such a solution has its limitations and implications. To overcome some of them one can leverage the benefits of cloud computing by using a combination of diverse private and public clouds. This approach is developed in Cloud Platform as federated cloud storage, where data is stored redundantly on various cloud storage services. The benefits are the following:

- **High availability** – data may be temporarily unavailable and/or corrupted for various reasons when system relies on a single cloud storage provider, as shown in recent cases (see section 2.3). In cloud federation we are able to store data redundantly and switch between providers when one becomes unavailable.

- **No vendor lock-in** – there is currently some concern that a few cloud computing providers become dominant, the so called vendor lock-in issue. Migrating from one provider to another one can also be expensive. In cloud federation we are able to easily switch between providers considering their charging or policy practices.

Federated cloud storage is not sufficient to provide data unavailability and corruption tolerance. For this purpose, an additional service has to be designed to actively monitor data integrity – DRI.

Access to the federated cloud storage is via common access layer – LOBCDER service – served by WebDAV protocol. However, DRI service will access cloud storage services directly to take advantage of cloud federation and to omit redundant LOBCDER overhead.

3.1.5. Atomic Service

In order to ensure smooth deployment for application developers, Cloud Platform creates a concept of Atomic Service. It can be simply described as a VM on which core components of the VPH-Share-specific application software have been installed, wrapped as a virtual system image and registered for usage within the platform. The process of creating new atomic service is depicted in figure 3.3. Typical application software installations provided by Atomic Service is federated storage access, web service command wrapper and web service security agent. Additionally, Cloud Platform takes care of instantiating various Atomic Services. Atomic Service Instance is a specific atomic service deployed on computing resources and providing VPH-Share application functionality through a web service (SOAP or REST) interface.

Services providing core functionality within VPH-Share will be also deployed as atomic service instances.

3.2. DRI data model

The Cloud Platform concerns itself primarily with access to binary data, especially via file-based interface. Managed dataset represents a single entity that can be managed. At its core, it consists of a selection of files, to which a portion of metadata is appended and stored in AIR reigstry. As data integrity is a crucial requirement of the platform, the datasets can be tagged for automatic data integrity monitoring (DRI).

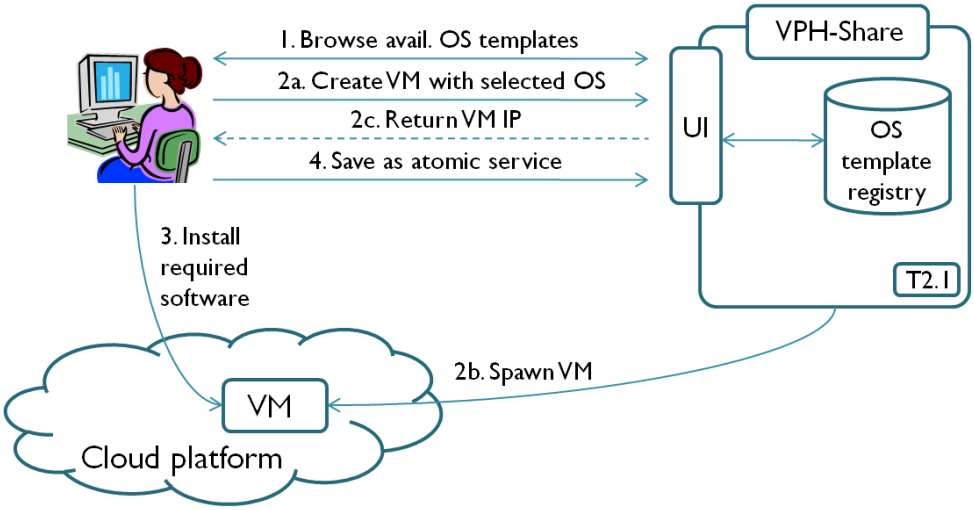


Figure 3.3: The process of creating and instatiating new Atomic Service [31].

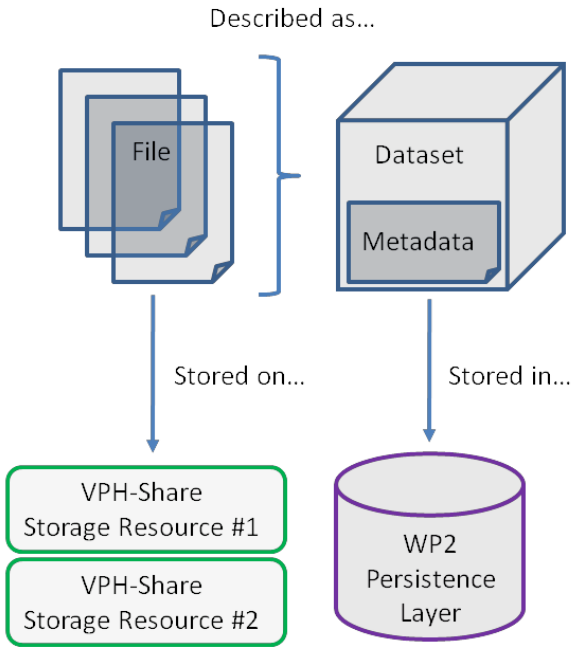


Figure 3.4: Schematic representation of VPH-Share managed dataset. Managed dataset consists of an arbitrary number of files (logical data) that are stored on one or more storage resources. The metadata regarding managed dataset is persisted in AIR [31].

3.2.1. Metadata schema

Each managed dataset may consist of an arbitrary number of files (logical data) and can be stored on one or more storage resources (data source). Specific security constraints can be attached to data items, i.e. it cannot be used in public clouds. In DRI component, validation checks are of configurable policy (management policy). The schema is depicted in the figure 3.5.

The managed dataset metadata consists of the following elements:

- **owner** – reference to user ID of dataset creator,

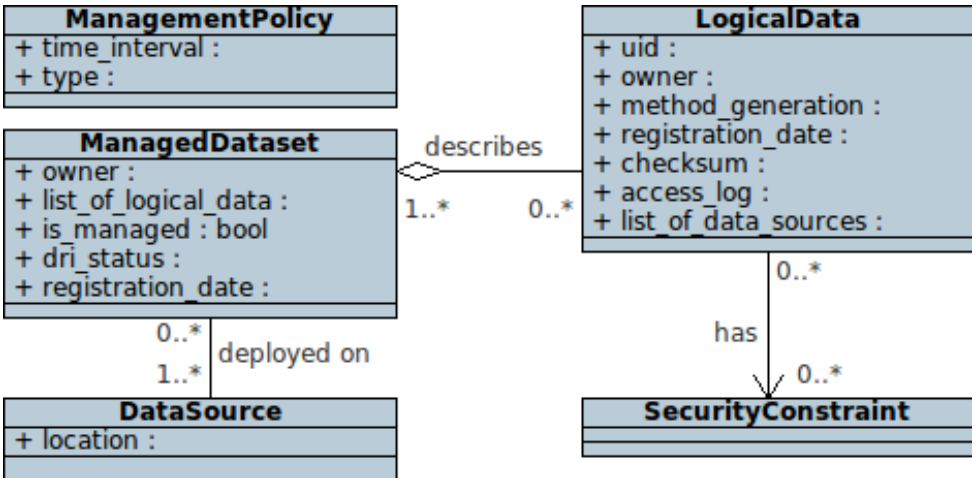


Figure 3.5: DRI service metadata schema. It generally reflects the concept of managed dataset presented in figure 3.4. Managed dataset consists of arbitrary number of logical data and is deployed on one or more data sources. Logical data can have security contraints attached to it. Additionally, a management policy can be attached to every managed dataset.

- **list of logical data** – list of logical data ids it consists of,
- **is managed** – marker determining whether dataset's integrity is monitored,
- **DRI status** – dataset's reliability and integrity status,
- **date of registration**.

Additionally, each logical data will consist of the following attributes:

- **owner** – reference to user ID,
- **method of generation** – whether it was uploaded manually, generated by an application or registered externally,
- **date of registration**
- **checksum** – file's value of a cryptographic hash function calculated upon registration and used to validate integrity and availability of file,
- **list of data sources** – to which the file is currently deployed,
- **access log**.

While this schema is expected to cover all the requirements addressed in the DRI service, we foresee that additional metadata can be added later without affecting already stored.

3.2.2. Tagging datasets

Before automatic verification of managed datasets can take place, it is first necessary to tag specific data as subject for management. It is foreseen that the DRI component will involve a user interface extension (portlet-based) to enable authorised users to tag specific datasets for automatic management. This interaface will display the existing data storage resources and allow creation of new managed

datasets consisting of selected files.

In addition to UI based tagging, the DRI component provides API-level access for the same purpose, whenever a VPH-Share application (or workflow) needs to tag specific data as a managed dataset.

3.3. Architecture

The DRI Runtime is responsible for enforcing data management policies. It keeps track of managed components and periodically verifies the accessibility and integrity of the managed data. It operates autonomously as well as on request. It also interacts and cooperates with the other important Cloud Platform's components (see section 3.1) to fulfill its goal. At the core of the service is an application that periodically polls the AIR registry for a list of managed datasets and then proceeds to verify the following:

- the availability of each dataset at locations read from the AIR registry,
- the binary integrity of each dataset (checksum-based validation).

The DRI Runtime contacts individual data sources and validates the integrity and availability of the data stored on these resources. Should errors occur, the DRI Runtime invokes a notification service to issue a warning message to subscribed system administrators (typically, the user defined as the dataset's owner).

3.3.1. Overview

The architecture of the DRI service was mostly influenced by the Cloud Platform environment (section 3.1) and the requirements and challenges it introduces (section 1.3.2). Figure 3.6 presents its overview.

The DRI Runtime consists of a couple of subcomponents which interact with each other as well as with other services described. It exposes REST service interface to be invoked by Master UI or the Atomic Services (see subsection 3.3.2 for details). MetadataAccess component is responsible for retrieving necessary metadata from the AIR registry. Access to the federated cloud storage is performed via FederatedDataAccess layer in order to hide the underlying complexity and differences between various cloud storage access. ValidationExecutor represents the core of the DRI. Its objective is to manage all the validation tasks, both periodical and requested by user. For each logical data it invokes ValidationStrategy component to perform its data validation algorithm.

3.3.2. Interface and API

As hinted upon in the preceding sections, DRI provides end-user interfaces in the form of a Master UI portlet, as well as an API implemented by the Runtime service, where DRI features may be invoked directly by other VPH-Share intrastructure components.

Here we intend to focus on the API, which provides access to the low-level functionality of DRI and enables it to be configured.

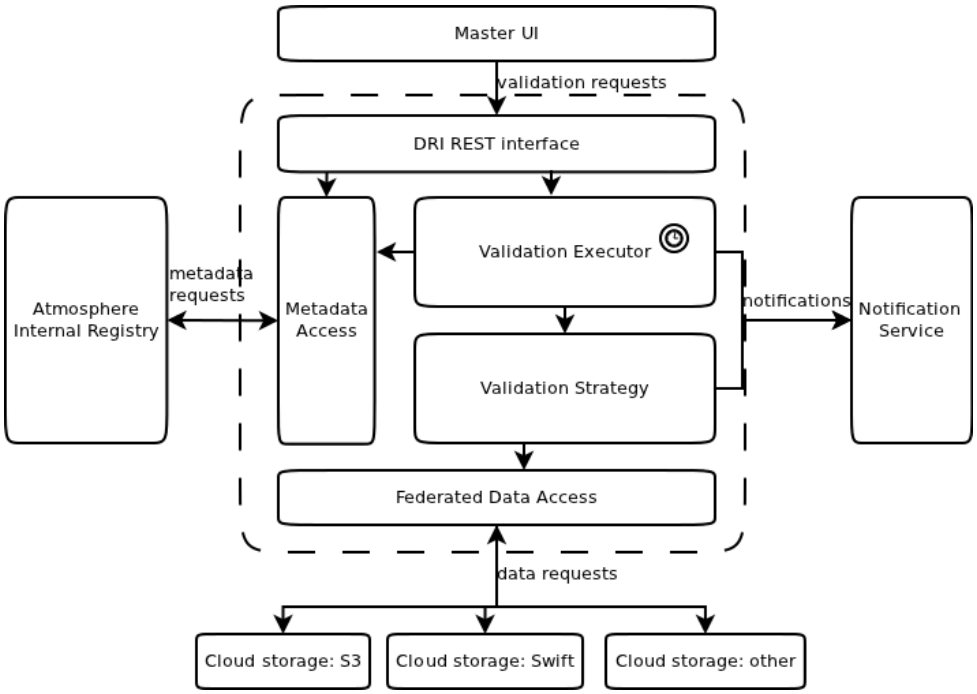


Figure 3.6: DRI architecture overview. It exposes REST API interface for other Cloud Platform components, mostly Master UI. The design is divided into modules that are responsible for providing separate functionality. ValidationExecution module is responsible for periodical as well as on-request based validation of datasets. All of the integrity metadata is provided through MetadataAccess module. The complexity of accessing different cloud storage providers is abstracted with FederatedDataAccess layer.

As DRI exposes a stateless Web Service, all configuration parameters are stored in the Atmosphere Internal Registry. Whenever a configuration change request is invoked the DRI automatically updates policies stored in AIR. In light of this, the DRI API supports the following operations:

- ***getDataSources(): DataSourceID[]*** – returns a list of currently registered data storage resource identifiers;
- ***getDataSource(dataSourceID): DataSourceDescription*** – returns the information on a specific storage resource, as stored in the Atmosphere Internal Registry in a form of XML document describing the structure of storage resource;
- ***registerManagedDataset(DatasetDescription) : datasetID*** – tags a new dataset for management given in the form XML document describing the structure of the dataset;
- ***alterManagedDataset(DatasetID, DatasetDescription) : void*** – changes the dataset specification stored in the AIR. This action should be used to add or remove files from a managed dataset;
- ***removeManagedDataset(DatasetID) : void*** – excludes the specified dataset from automatic management. This does not delete the data, it merely stops DRI Runtime from monitoring them;
- ***getManagedDataset(DatasetID) : ManagedDatasetDescription*** – requests information on a specific managed dataset stored in the AIR, returning XML document specifing the structure of the managed dataset;
- ***getOwnerManagedDataset(User) : DatasetID[]*** – returns a list of user's managed dataset ids;

- ***assignDatasetToResource(DatasetID, DataSourceeID) : void*** – requests DRI to monitor the availability of a specific managed dataset in a specific storage resource. If this dataset is not yet present on the requested storage resource, it will be automatically replicated there;
- ***unassignDatasetFromResource(DatasetID, StorageResourceID) : void*** – requests DRI to stop monitoring the availability of a specific managed dataset on a specific storage resource. If the dataset is not present on the selected storage resource, this action has no effect;
- ***validateManagedDataset(DatasetID) : output*** – performs asynchronous validation of the specific dataset and produces a document which lists any problems encountered with the dataset's availability on the storage resources to which it had been assigned;
- ***setManagementPolicy(ManagementPolicy) : void*** – changes monitoring parameters. ManagementPolicy is an XML document specifying the frequency and type of availability checks performed on managed datasets;
- ***getManagementPolicy() : ManagementPolicy*** – retrieves an XML description of the management policy.

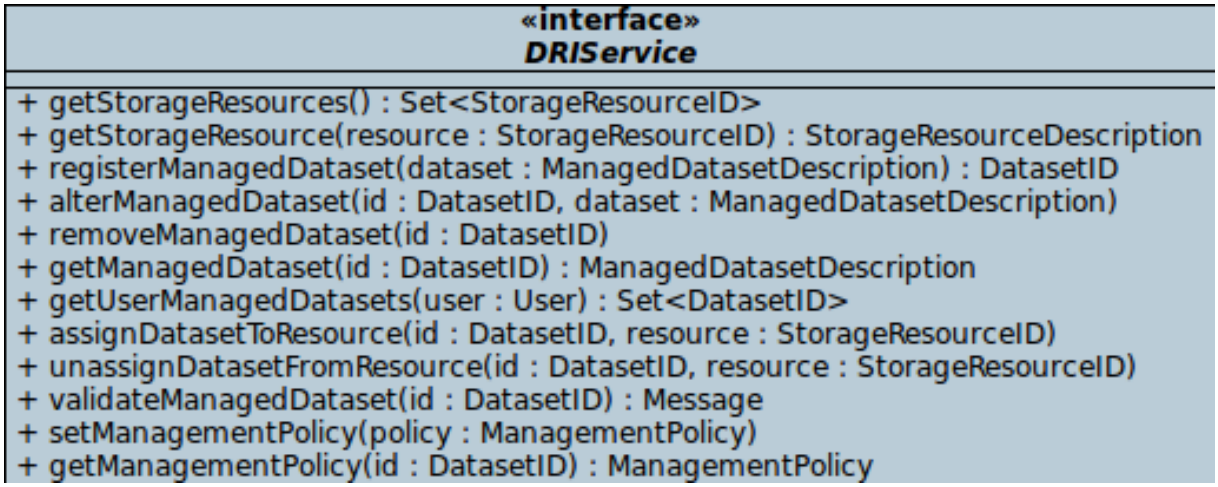


Figure 3.7: DRI Service interface. It provides flexible set of methods to manipulate integrity monitoring of datasets.

Each invocation requires to be augmented by the security token which can be intercepted and parsed by the security component residing on the virtual machine on which the DRI Runtime operates.

3.3.3. Typical use cases execution flow

The two main tasks performed by the DRI is monitoring of data integrity and replication of managed datasets among various data sources. Now, we will present a typical execution flow for this tasks through DRI subcomponents presented in figure 3.6 using sequence diagrams.

We start with data validation illustrated in figure 3.8. The *validateManagedDataset()* method is the one designed to be called by the user, however, the incorporated logic for periodic integrity checks is the same, as ValidationExecutor fetches all the managed datasets from AIR and invokes this operation for each of them.

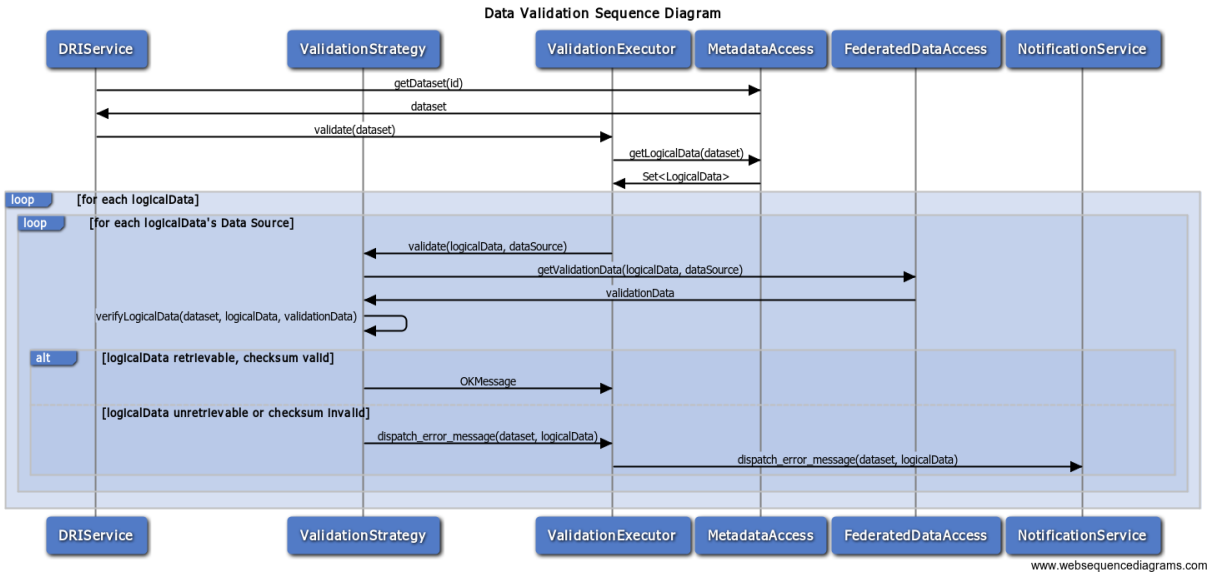


Figure 3.8: DRI *validateManagedDataset()* call sequence diagram

Upon *validateManagedDataset()* call, the DRI service retrieves dataset's metadata from AIR registry invoking *getDataset(id)* on MetadataAccess object and passes it to the ValidationExecutor to apply data availability and integrity check. Subsequently, ValidationExecutor retrieves the metadata of all the logical data items which are part of the specified dataset invoking *getLogicalData(dataset)* on MetadataAccess. Validation occurs separately for each logical data and against every data source on which it is stored by ValidationStrategy object which implements efficient validation protocol. To perform this operation, it has to get some necessary portion of data from data source by calling *getValidationData(logicalData, dataSource)* on FederatedDataAccess object. With this necessary data, ValidationStrategy can verify whether the specified logical data is available and valid. If not, the error message is dispatched via NotificationService. It incorporates all or nothing strategy, which means that the corruption of a single logical data results in marking whole dataset as invalid. However, detailed error message informs which items' corruption has been detected on which data sources. The *validateManagedDataset()* call performs asynchronously (no return value), but the result of the operation can be checked via NotificationService.

Upon *assignDatasetToResource()* call (figure 3.9), the DRIService retrieves dataset's and data source's metadata from AIR registry invoking *getDataset(id)* and *getDataSource(source)* on MetadataAccess object and passes it to the ReplicationExecutor. If dataset is already present on the specified location, this operation has no effect. Subsequently, ReplicationExecutor checks all the constraints, via *check(dataset, dataSource)* call, that may be associated with the dataset (such as it cannot be stored in public clouds) and if they are valid, it performs the replication. This operation simply copies data from one data source on which the dataset is already present to the specified data source. In case of any failures, the operation aborts with no side effects. Upon successful execution, the necessary dataset metadata is updated in AIR registry (*updateDataset(dataset)* call).

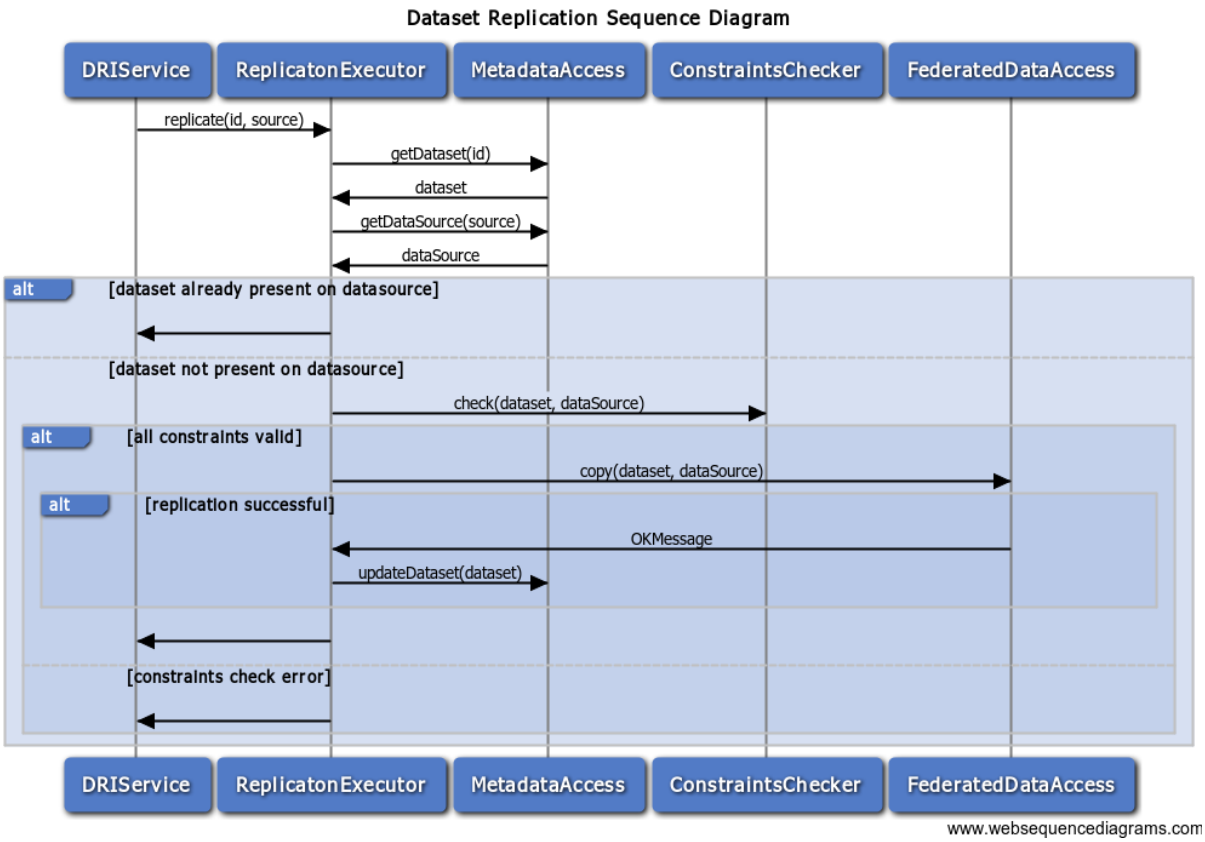


Figure 3.9: DRI *assignDatasetToResource()* call sequence diagram

3.4. Data validation mechanism

At the heart of DRI service lies its validation heuristic algorithm which is going to be described now in detail. As it was discussed in chapter 2, a lot of effort was put into ensuring data integrity and availability on storage resources. However, cloud storage model sets new challenges in this area due to its constraints and limitations presented in section 2.3. The problem was addressed in the papers described in section 2.4, one of which - Proofs of Retrievability - became the basis for many enhancements, modifications and improvements. Each of the solution approaches difficulties with vast amount of data stored on cloud storages by creating sophisticated protocols which download only a fraction of data $(1 - 10\%)$ and try to guarantee possibly the highest error-detection rate. Unfortunately, introduced solutions do not address performance issues of these protocols with regard to typical cloud storage interfaces and VPH-Share platform requirements:

- requesting many small fragments of data greatly affects network overhead as each fragment requires separate HTTP request,
- cloud storages do not allow executing users' code,
- VPH-Share platform requires storing data in unmodified form.

These limitations make these solutions impractical. For the needs of DRI service, a new approach was designed with practical feasibility and low network overhead as main objectives in mind. Our heuristic utilizes spot-checking technique to verify data integrity with high probability. Unlike cited mechanisms

```
   Data: valid dataset id
   Result: true if dataset valid, error messages otherwise
 1 dataset = get_dataset_metadata(id);
 2 files = get_dataset_files(dataset);
 3 for file in files do
 4     for data_source in dataset.get_data_sources() do
 5         data = get_validation_data(file, data_source);
 6         if data == null then
 7             dispatch_error_message(file, data_source);
 8         end
 9         result = validate_data(data, file, dataset);
10         if result is invalid then
11             dispatch_error_message(file, data_source);
12         end
13     end
14 end
```

Algorithm 1: Dataset validation algorithm

[37,41] which generally implement fine-grained spot-checking, we are aware of cloud storage limitations and employ coarse-grained spot-checking, realizing that it will result in reduced error-detection rate.

3.4.1. Algorithm description

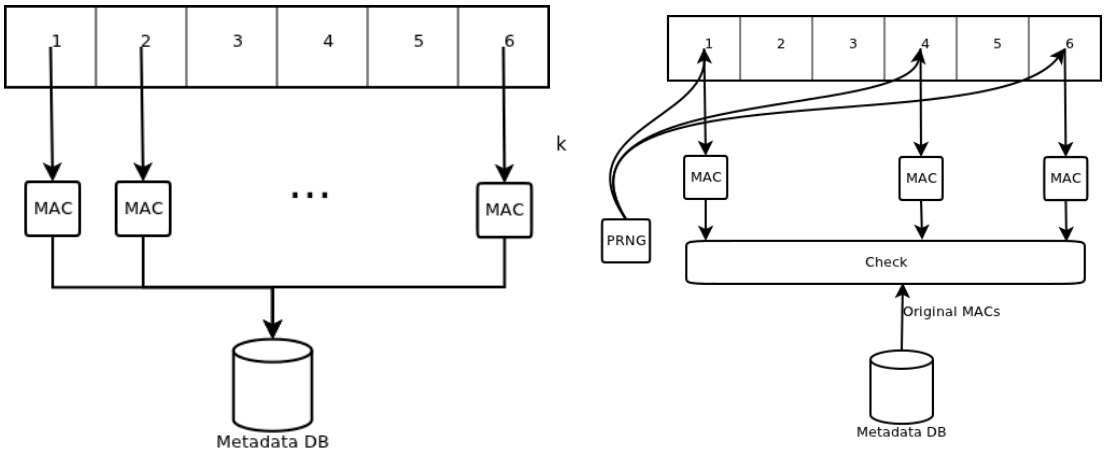
According to the data model described in section 3.1, dataset is a set of files stored on cloud storage resource. To be able to validate dataset's integrity, it is firstly necessary to retrieve dataset's data, then compute and store some checksum metadata for each file. During the validation process, the dataset's data is retrieved and checksums are computed again to compare them with the original ones. The algorithm 1 illustrates the pseudocode of this operation.

To validate a dataset, the metadata of it and all the files it consists of have to be retrieved (lines 1–2). Then, each file is validated against every data source it is stored on (lines 3–4). To validate a single file, the algorithm retrieves its necessary data (line 5). If errors occur, the file's unavailability message is reported (lines 6–8). Otherwise, integrity checksum is computed and checked with the original one (line 9). Any resulting integrity error is reported (lines 10–12).

The core part of the validation mechanism is the validation algorithm (validation protocol) which prepares dataset's metadata and then is able to validate it. As a typical integrity checking algorithm it comprises of two phases:

(1) **setup** – takes place once (or after each file update) and generates checksum used during every validation phase. During this phase the file is divided into n chunks of size $\frac{F}{n}$ (where F denotes the size of entire file) and MAC hash is computed for every data chunk. Then, a set of n checksums is stored in metadata registry for further use.

(2) **validation** – takes place on every dataset validation request. During this phase, the file is again divided into n chunks of size $\frac{F}{n}$ and pseudorandom number generator selects k out of n chunk



(a) Setup phase

(b) Validation phase

Figure 3.10: Single file validation heuristic consists of two phases: setup and validation. In setup phase (a), the file is divided into n chunks and MAC hash is computed for every data chunk which is then stored in metadata registry. In validation phase (b), the file is again divided into n chunks and pseudo-random number generator selects a set of k out of n chunk indexes that are downloaded, their checksums computed and compared with the original ones stored in metadata registry.

indexes that are downloaded and their checksums computed. Then, computed checksums are compared with original ones stored in metadata registry.

These phases are graphically presented in figure 3.10.

Values k and n are configurable and can be set to fulfill specified requirements. The greater the value of n, the smaller the chunks are (see setup phase description) and more separate k HTTP requests need to be sent to maintain demanded error-detection rate. With fixed n, the greater the value of k, the higher error-detection rate.

Datasets consisting of large number of small files can lead to the performance bottleneck for two reasons: many separate HTTP requests for each small file and big storage overhead as chunks are small for small files, but for each a MAC checksum is stored. For this reason, one additional parameter $threshold$ was introduced to improve performance over small files. Data integrity for files of size smaller than $threshold$ is provided by classic entire-file SHA-256 checksum. The value of $threshold$ parameter will be established empirically based on performance test results presented in chapter 5.

3.4.2. Algorithm analysis

Validation algorithm described in the previous subsection is rather simple in its design, but poses properties that make it practically feasible:

- files are stored in unmodified form,
- network overhead and number of HTTP requests can be configured by n and k parameters,
- error-detection rate can be configured by n and k parameters.

Detailed algorithm description enables theoretical estimation of the most interesting properties that characterize our solution:

- **Error-detection rate** – expresses the probability to detect data corruption. For small changes, its value is equal to the probability that the change took place within the k blocks that are verified:

$$E_{det} = \frac{k}{n} \qquad for\ small\ changes. \tag{3.1}$$

  However, if the prover has modified or deleted substantial e-portion of F, then with high probability, it also changed roughly an e-fraction of chunks.

- **Network overhead** – expresses the fraction of data that has to be retrieved in order to verify the integrity on desired level. As in our scheme, we download k out of n chunks (each of size $\frac{F}{n}$), the network overhead value is proportional to:

$$N_{over} \sim F \times \frac{k}{n}. \tag{3.2}$$

- **Execution time** – expresses the time needed to validate a file of size F. It depends on average network download speed, as well as on network latency to the cloud provider. Each HTTP request introduces latency, so the more requests are sent, the more network efficiency is affected. We estimate this value in the following way: each chunk of size $\frac{F}{n}$ is downloaded in $\frac{F}{n \times speed}$ time (where $speed$ is download speed in bits/s) plus additional request latency time. As we validate k chunks per validation phase, we get the execution time:

$$T_{exec} \sim k \times (\frac{F}{n \times speed} + latency) \tag{3.3}$$

  However, the latency factor can be drastically reduced by performing a set of HTTP requests concurrently.

Metric	our approach	whole-file approach
E_{det}	$\frac{k}{n}$	1
N_{over}	$\sim F \times \frac{k}{n}$	$\sim F$
T_{exec}	$\sim k \times (\frac{F}{n \times speed} + latency)$	$\sim \frac{F}{speed} + latency$

Table 3.1: Performance metrics comparison between our and whole-file approaches

In table 3.1 we summarize the three metrics values for our approach in comparison with whole-file validation approach. Practical performance evaluation with varying values of the parameters n, k and $threshold$) and in the real cloud storage environment is presented in chapter 5.

3.5. Summary

This chapter presented in-depth the design and architecture of data reliability and integrity (DRI) service. The architecture of the VPH-Share Cloud Platform was introduced to provide a context in which DRI is developed and that mostly influenced its requirements. Given that, we determined the DRI data model and formulated its – functional and non-functional – requirements. The API of the service tries to

reflect all of the identified use cases.

At the end, we presented the design of the network efficient algorithm that tries to take cloud storage limitations into account and provide means of network efficient corruption detection on some level of probability. The concept is based on POR and DIP schemes presented in section 2.3. Finally, we presented the equations describing the algorithm features.

4. DRI implementation

In the previous chapter, DRI Service architecture was described. In the following, we present the way how we have implemented it. We also discuss the technologies that were used for the separate parts of the service. At the end we briefly descibe how it could be used outside of the VPH-Share Cloud Platform and integrated in other environment.

4.1. Overview

Implementation of a large software system typically involves some set of technological or paradigmatic assumptions that have to be taken into consideration while implementing its components. VPH-Share Cloud Platform takes advantage of SOA paradigm. All of the components are designed as loosly-coupled web services that cooperate via REST interfaces. As a result, each component may theoretically be implemented using any technology stack. However, to avoid excessive diversity of software technologies, most of them are implemented in Java or Ruby programming languages, the practically proven open source solutions.

As it was mentioned in section 3.1, all of the Cloud Platform's core services will be deployed within Atomic Service instances, a VPH-Share application container. Atomic Service can be simply viewed as VM with add-on software and mechanism installed, such as security or federated data access layers.

DRI Service implementation was conducted according to the architecture described in chapter 3 with the best software development practices, such as testing and design patterns in mind. The main goal is to achieve the highest possible data validation efficiency, while providing an acceptable probability of unavailability or error detection. The design of DRI Service already solved some performance issues, mostly on the validation algorithm. However, implementation details have to be taken into account.

4.2. Challenges and decisions

It is a recurring engineering truth, that practical implementation to some degree always affects the design. Ideally, project's implementation should accurately reflect its design. However, different technology stack choices vary significantly, from programming language paradigm and available contructs, to best practices and design patterns, to available libraries and their specifics. Therefore, DRI architecture presented in chapter 3 represents only the the conceptual and functional view of the service.

With DRI Service architecture design we clearly identified the biggest software engineering challenges that have to be addressed in the implementation. There are the following:

- creating REST web service interface (REST producer),
- REST interoperability with other components (REST consumer),
- federated cloud access to various cloud storage providers (often non-compatible interfaces),
- periodic job execution and scheduling,
- loose coupling between the subcomponents (facilitates configurability and reuse).

We have also foreseen, that Cloud Platform components will be changing rapidly their interfaces and remaining up-to-date will require a lot of integration testing. It was addressed partially in the DRI architecture, where all of the external service interactions are wrapped into easily interchangable interfaces (MetadataAccess for example). Moving with the times, DRI Service implementation was made according to test driven development (TDD [22, 38]) approach to software engineering. Broad set of integration sets created this way allowed to spot changes in other components.

4.3. Implementation technologies

Java programming language [19] was chosen as implementation language and technology stack. Advantages are significant, Java:

- proved to be high-performance and commercially proven,
- has a vast number of libraries available,
- has big and active community,
- has wealth range of developer tools.

At its core, DRI Service is a Java Servlet [44] component which accepts REST requests on specified URI paths and performs the requested task utilizing MetadataAccess, ValidationExecutor, ReplicationExecutor, ValidationStrategy and FederatedDataAccess, implemented as simple Java objects. In Java Servlet model, the programmer is free of the object's lifecycle management and REST/HTTP communication complexities, which is provided by the container into which application is deployed.

Another important implementation's aspect is dependency injection (DI [32, 46]). It is a software design pattern which releases the programmer from "dependency-hell" problem. It removes the need to provide dependencies (object instances) when constructing objects, which is error-prone. Dependencies are provided dynamically by the DI container at runtime according to the configuration. In DRI, we use Guice library [6] for DI capabilities. DI approach significantly simplifies component's testing in a service-based environment as dependable service can be simply swapped with a mock object in the configuration.

DRI Service components implementation technologies are depicted in figure 4.1. Further subsections describe them in detail.

4.3.1. REST interfaces

To provide REST interface and cooperate with other Cloud Platform components, DRI utilizes Jersey library [8] – a reference implementation of the JAX-RS specification [35] and supports seamless

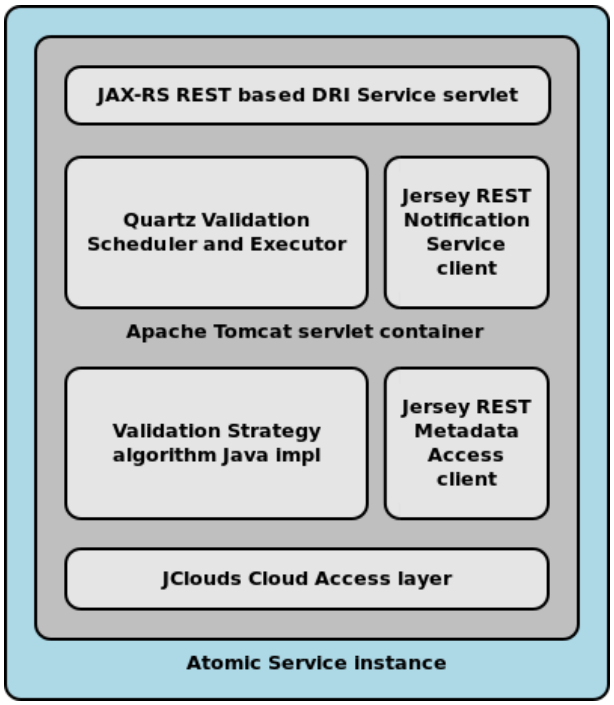


Figure 4.1: DRI Service implementation technologies of its modules. REST API interface is provided using JAX-RS technology. Federated data access is built on JClouds library which abstracts the complexity of accessing different cloud storage providers. Jersey REST client library eases the integration with REST based services on which DRI depends. Finally, in batch execution DRI utilizes Quartz library.

integration with Java Servlet technology. It provides both, server and client REST interoperability via Java annotations [34].

Server side

In JAX-RS to create a REST interface for DRI it is as simple as the following: Creating JAX-RS based REST service interfaces is very simple. The following listing shows a part of the DRIService interface:

```
@Path("/driservice")
public class DRIService {
        @PUT
        @Produces(APPLICATION_JSON)
        @Path("register_managed_dataset/{datasetId}")
        public void registerManagedDataset(@PathParam("datasetId") String datasetId) {
                // method body omitted
        }

        @POST
        @Produces(APPLICATION_JSON)
        @Path("validate_managed_dataset/{datasetId}")
        public void validateManagedDataset(@PathParam("datasetId") String datasetId) {
                // method body omitted
        }

        @GET
        @Produces(APPLICATION_JSON)
        @Path("get_managed_dataset")
```

```
        public ManagedDataset getManagedDataset(QueryParam("datasetId") String datasetId) {
                // method body omitted
        }

        // Further methods follow...
}

@XmlRootElement
public class ManagedDataset {
        @XmlElement(name = "name", required = true)
        private String name;

        @XmlElement(name = "size", required = true)
        private Long size;

        // Further members follow...
}
```

To make your Java method available through REST you simply annotate the class and its methods with JAX-RS annotations. Let us take *getManagedDataset* method as an example. It will

(1) be available under */driservice/get_managed_dataset/datasetId* URL, where *datasetId* is a string part of the URL specifying dataset id (*Path* annotation),

(2) be accessible via HTTP GET method (*GET* annotation),

(3) produce HTTP JSON format output (*Produces* annotation).

The format of the *ManagedDataset* JSON method output is mapped into Java object via *XmlRootElement* and *XmlElement* JAXB annotations [51].

Client side

Creating Jersey based client of the REST service is also straight-forward:

```
public class AIRMetadataRegistry {
        @Inject @Named("air-config")
        protected WebResource service;

        public List<ManagedDataset> getManagedDatasets() {
                return service
                        .path("/get_datasets")
                        .queryParam("only_managed", Boolean.TRUE)
                        .get(new GenericType<List<ManagedDataset>>() {});
        }

        // Further methods follow...
}
```

Here, we use already configured *WebResource* object to build REST query to *BASE_URL/get_datasets* URL with *only_managed* query parameter. Jersey automatically deserialize the returned response into *ManagedDataset* object we presented in the previous listing.

4.3.2. Cloud storage access

Current cloud storage services mostly provide a standard REST interface. Despite interface similarities, it appears cumbersome to support the differences between providers. To get rid of this problem, DRI uses JClouds [7] library that provides a common API layer that abstracts cloud dissimilarities. Thus, access to the cloud storage federation is quite easy via programmer perspective. At the time of writing this thesis, JClouds supports up to 30 different cloud providers including Amazon, GoGrid, vCloud, Openstack, Azure and others. Storage access is provided as Blobstore API, which incorporates three concepts: service, container and blob. The Blobstore is a key-value store such as Amazon S3, where your account exists and where you can create containers. A container is a namespace for you data and many of them can exist. Blob is an unstructued data stored in a container referenced by its name. In all cloud storages, the combination of the account, container and blob relates directly to the HTTP URL. Access to data can be performed synchronously or asynchronously, depending on the selected Blobstore type. While Blobstore API provides cloud storage abstraction it cannot overcome specific cloud provider's limitations, for example size limits or timeouts between sensitive operations.

JClouds's Blobstore abstraction provides uniform interface to different cloud storage providers. To use provider *X* one have to create *BlobStoreContext* for *X*. The following snippet simply shows how to access Amazon S3, create a container and put a blob into it:

```
// init
BlobStoreContext context = ContextBuilder
                            .newBuilder("aws-s3")
                            .credentials(accesskeyid, secretaccesskey)
                            .buildView(BlobStoreContext.class);

BlobStore blobStore = context.getBlobStore();

// create container
blobStore.createContainerInLocation(null, "mycontainer");

// add blob
Blob blob = blobStore
            .blobBuilder("test")
            .payload("testdata")
            .build();
blobStore.putBlob("mycontainer", blob);
```

4.3.3. Task scheduling

DRI Service periodically monitors data integrity. Periodic tasks invocation is a recurring issue in many IT systems. DRI uses Quartz library [10] for task scheduling and execution. Quartz is a full-featured open source job scheduling library that can be integrated with, or used along side virtually any Java application – from the smallest to the largest e-commerce system. Its main highlights are the following:

- periodic and timer jobs,
- configurable executors (single thread or pool of threads),
- templates for creating job task objects,
- support for job transactions and persistence,

- scalable – from simple to complex schedules for executing tens, hundreds or even ten-of-thousands of jobs,

DRI Service uses Quartz in the following way: at startup it schedules main (root) periodic job with specified period, which upon trigger, is responsible for scheduling one validation job per managed dataset. Apart from periodic validation, the dataset's integrity check can be performed on request. In such case, DRI tries to add validation job for the specified dataset to the schedule. If a job with the same dataset id already exists in the queue, nothing happens (double validation is not desired). Otherwise, the job with specified dataset id is added to the schedule. Worth mentioning is the fact, that apart from validation jobs, there are jobs that update dataset checksums whenever its contents changed and both of them cannot collide with each other. Upon job execution, a *JobDetail* is returned.

4.4. Data validation implementation details

DRI Service utilizes efficient data validation algorithm to achieve acceptable performance over large amount of data. However, apart from algorithm efficiency, its optimized implementation is greatly desirable. Due to the fact that the validation algorithm is highly oriented on network communication (see section 3.4), network bandwidth and latency are the most significant factors affecting its performance. The point of the biggest interest is access to large number of the selected chunks of data. As it was noted in section 2.2, current cloud storage interfaces do not enable efficient way to perform this operation. However, even though individual chunks of data have to be requested in separate HTTP calls, they can be invoked asynchronously in parallel to reduce round-trip time (RTT) latency. DRI employs this scheme via asynchronous Blobstore API provided by JClouds library. When DRI validates single logical data within dataset, it invokes a configurable number of asychronous data chunks requests and then waits for their completion. The scheme repeats until all the needed chunks for logical data are collected.

4.5. Deployment environment

Currently, at proof of concept stage, the DRI is deployed on Apache Tomcat [3] instance which runs on virtual machine (VM). However, in full-operational Cloud Platform it will be deployed within Atomic Service instance (simply a VM with some add-ons) as one of its core services. Apache Tomcat is a web application container which implements Java Servlet specification and provides its application environment. Nevertheless, any other application server compliant with Java Servlet specification can be used.

4.6. The use outside of Cloud Platform

DRI Service component could be successfully used outside of the VPH-Share Cloud Platform frame. By design, its dependent components are used through abstraction layers and could be easily swapped to accomodate to other environment. Metadata could be stored on cloud storage or local disk file; Notification Service could be implemented as a mail sender or chat client – every such change requires only to modify one package (see figure 4.2. Moreover, many of the configuration parameters such as: REST urls, credentials, federated cloud metadata etc, are kept in configuration file and can be easily changed.

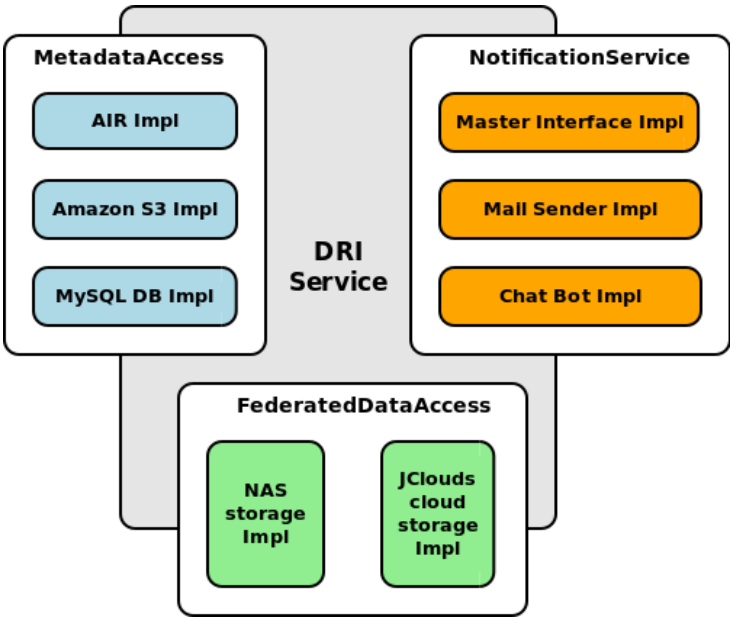


Figure 4.2: Possibility to switch DRI service providers by reimplementing abstraction layer and accomodate to new environment, other than VPH-Share Cloud Platform

4.7. Scalability

It is foreseen, that with the growth of the platform it could be necesarry for DRI to provide scalable solution. Hopefully, by design, DRI is a stateless web service so the simplest solution would be to run a couple of its instances and provide requests load balancing between them. Another possibility, as DRI uses Quartz for job scheduling and execution, would be to build Quartz cluster and make DRI submit its validation jobs to it. Lastly, single dataset (or even single file) validation is completely independent from one another, meaning that scalability issues can be easily addressed.

4.8. Summary

This chapter presented the way DRI service was implemented based on its design and requirements described in the previous chapter. It outlines the choice of Java technology stack and additional libraries and justifies it. JClouds library helped us to address one of the main implementation challenges to abstract cloud storage access and get rid of cloud provider interface differences. Additionally, JAX-RS, Guice and Quartz enabled us to create the skeleton of DRI implementation relatively fast and without complications. At the end we also discuss the possiblitity to use DRI outside of VPH-Share platform. To achieve this, one has to reimplement the abstract layer through which DRI accesses external services. On the other hand, scalability can be easily achieved by small modifications through running multiple instances of DRI service and pinning datasets periodical validations to concrete instances.

5. Verification and testing

This chapter presents the evaluation of DRI service which design and implementation was described in the previous chapters. It starts with the description of a test case study that is used for this purpose. It aims to cover the crucial service functionalities. Then, a service test environment is discussed. In order to ease evaluation process a notification service mock has been created. Finally, in the following sections, the subsequent service requirements are evaluated.

5.1. Test case scenario

As a case study for DRI evaluation we designed a test scenario consisting of multiple data manipulation steps within VPH-Share project. Thanks to administration rights to the data stored on Openstack instance we were able to manually simulate data corruption and unavailability issues. The test case consists of the following steps:

(1) creating a dataset and uploading initial archive data through VPH-Share federated cloud storage access layer,

(2) tagging newly created dataset as managed,

(3) waiting for success notification (no errors) about previous step,

(4) invoking on-request validation of the dataset,

(5) waiting for successful dataset validation,

(6) manuallly modifying dataset content,

(7) invoking on-request validation for the second time,

(8) waiting for integrity error – data corruption,

(9) manually erasing file from the dataset,

(10) invoking on-request validation for the third time,

(11) waiting for integrity error – data unavailable.

In step 6 the content of the dataset is modified in two different ways – every byte of the file is changed and only a fraction of the file is changed. Corruption detection always succeds in the first case, while the second allows false positives to occur when using probability-based validation algorithm.

This scenario represents a relatively easy test case. However, it is an excellent candidate for automation in form of an integration test that runs during every new build of the component. To automate it, we either need an integration test environment or such environment has to be mocked at runtime.

5.2. Deployment environment and configuration

In order to evaluate DRI, the service was deployed in the production environment of VPH-Share project. During the prototype phase, a dedicated virtual machine running Linux server with Apache Tomcat is used instead of Atomic Service instance. The deployment of DRI comes down to uploading a web application archive (WAR) to Tomcat server instance. DRI at the time of writing this thesis provides REST interface (described in detail in section 3.3.2) at `http://vph.cyfronet.pl:18080/driservice/`. For testing purposes DRI was provided with two cloud storage providers, Amazon S3 account and private instance of Openstack Swift infrastructure.

DRI periodical validation period was set to $30min$. The validation algorithm parameters – k and n – were set to 10 and 100 respectively. This means that each file is divided into 100 blocks of equal size. The checksum of every block is stored in metadata registry upon tagging file as managed. During the validation phase, only 10 randomly selected blocks (roughly 10% of the file size) are retrieved, their checksums computed and compared with the original values. Such configuration ensures error detection rate on relatively low level of probability, 10% for small size modification e (where $e \ll |F|$). However, it is proportional to the size of the modification when $e \sim |F|$ (see section 3.4.2).

5.3. Notification Service

At the time of writing this thesis, VPH-Share Cloud Platform still lacks usable notification service mechanism. In order to enable DRI evaluation we created a simple web page which mocks notification service functionalities – see figure 5.1. Its intent is to display basic information about operations perfomed by DRI service. It is organized in tabular view of notifications. A notification is represented by one row and is always associated with operation performed on single dataset. Each row consists of the following information:

(1) **dataset name**,

(2) **notification status** – a short message informing whether operation succeded or failed,

(3) **execution time** – the time it took to perform the operation in seconds,

(4) **time scheduled** – the time when the operation started.

It is available at `http://vph.cyfronet.pl:18080/driservice/notification.jsp`.

Additional notification details are available for failed operation when it is expanded. It can be seen which files within the given dataset caused problems – either they are invalid or unavailable. For instance, the expanded *dri_sample_dataset* notification shows that two files are unavailable – *earth.jpg* and *moon.jpg* – and the *time-machine.txt* is corrupted.

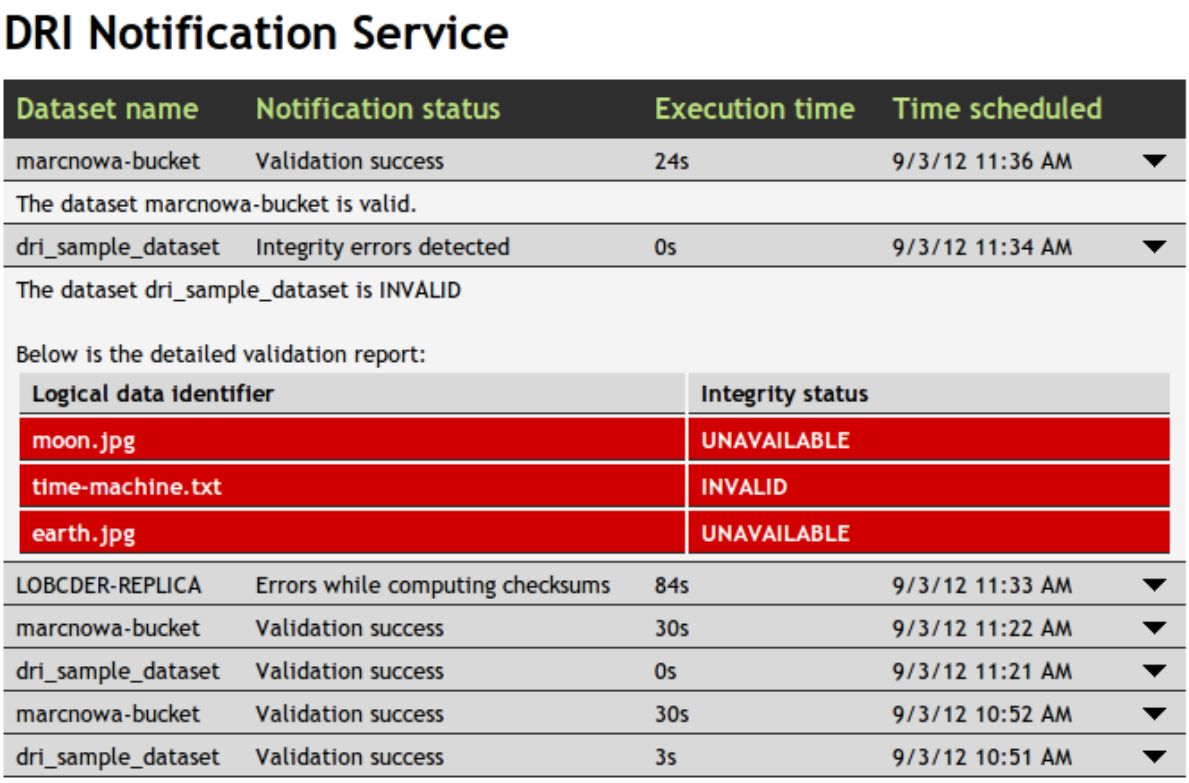


Figure 5.1: Notification service mock overview – it was created to evaluate DRI functional requirements. Notifications are organized in tabular view with basic information about the operation perfomed on a single dataset. The details of data integrity errors – whether containing file is invalid or unavailable – are presented after expanding each row.

5.4. Requirements evaluation

A key aspect of the DRI service is to meet its requirements within Cloud Platform, which were listed in section 1.3.2. In the prototype phase, we focus on data validation. As project continues, data replication mechanisms will be developed within DRI service. As previous chapters shown, we designed and implemented a service which enables periodic and on-request data validation and notifies about any integrity or availability errors. It can be used according to the REST interface described in chapter 3.

5.4.1. Essential data validation mechanisms

The current state of the DRI service provides a flexible set of methods to perform data integrity validation activities. At its core, it periodically and on request performs data validation of the datasets tagged as managed. From the user perspective, it supports tagging (untagging) given dataset as managed and provides various notification messages about the performed operation.

The execution of test case scenario is presented in figure 5.2. Each of the operation perfomed against DRI interface represents a single row. The *test_dataset* was successfully tagged as managed and no integrity errors occured during the first validation pass. After manually deleting and modyfing three files within the dataset, the second validation pass discovered data integrity errors. However, only partial changes to the *earth.jpg* file were not discovered. Hopefully, the third validation invocation managed to

discover all of the integrity issues that were maliciously introduced during the test scenario.

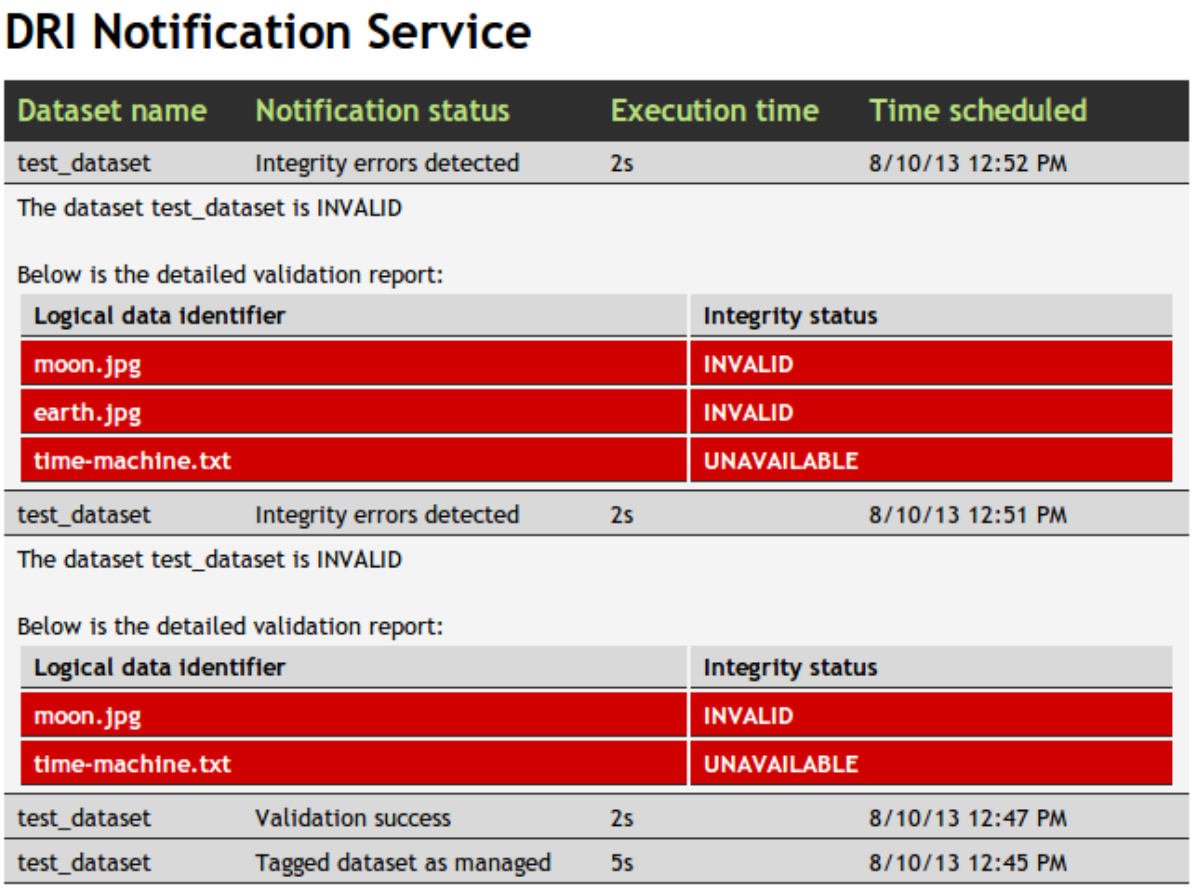


Figure 5.2: DRI service test scenario evaluation: intially a sample dataset with content was created. Upon successfully tagging it as managed no integrity errors are detected. After malicious files modification DRI was able to detect data corruption and unavailability. However, not every content change was discovered in every validation pass.

5.4.2. Data replication

In the VPH-Share Cloud Platform prototype phase, the emphasis is put on providing data availability and integrity. As project continues, data replication mechanisms will be developed with focus on providing data replication over multiple cloud storage providers as well as on-demand corruption recovery from existing replicas.

5.4.3. Configurability and scalability

Upon the deployment of DRI service it is provided with configuration file where administrator can specify core parameters. The main two of them are validation period and validation algorithm parameters – k and n. During test scenario we were able to set validation period to $30min$ and observer that all of the datasets tagged as managed are periodically validated with this period. With k and n parameters we could adjust the compromise between network overhead and error detection rate. Configuration sets these parameters globally for all datasets. It could be beneficial improvement to add the possibility to specify them per managed dataset upon tagging it as managed – via *management policy*.

5.5. Summary

This chapter presented the evaluation of the DRI service against the specified requirements. A special test scenario was designed to perform this. It aims to cover most of the core functionalities that DRI should provide. In order to present the results of the evaluation a simple mock of notification service in form of a web page was created. Due to on-going developement of VPH-Share Cloud Platform the evaluation was successful only partially. At the current stage of the project DRI provides all the necessary functionalities regarding validation of data availability and integrity, however it still lacks data replication mechanisms. This issue is going to be addressed in the second phase of the project.

6. Summary and future work

The main objective of this thesis was creation of a data reliability and integrity (DRI) service that monitors the availability and integrity of data stored on heterogeneous cloud storage resources. As it was shown, the resulting advantages of moving the data to the cloud suggest that widespread use of cloud storage seems inevitable. However, this new approach is not free from dangers. Recent cloud provider failure and malicious corruption reports [30] show that one cannot fully entrust the data to the cloud provider. But cloud storage brings new challenges for ensuring data security. Therefore, computer industry seeks for innovative tools and methods that could lower the risk associated with the current trend. The idea oscillates around harnessing multiple cloud storage providers and replicate the data among them. This approach creates a new layer of abstraction in accessing the data – cloud storage federation. While storing many copies of data on different cloud providers significantly reduces the risk of data loss, it is still needed to detect data problem. Hash-based checksums and error correcting codes are the industry standard methods of ensuring data integrity. However, cloud storage introduces obstacles against applying them, because data is stored remotely and cloud providers charge fees for outbound network transfer. As a result, for instance, validating a file by computing its SHA-512 hash based on the full content of it can significantly raise operational costs. Additionally, network latency and throughput affect the data access.

In this work different approaches for ensuring data integrity in cloud storage were presented. On-going research effort focuses on selectively validating the content of data and detecting corruption only on some level of probability. Discussed validation schemes propose different improvements of the outlined approach such as encrypting the content of data or they assume the existence of the element that performs computation on data without transfering it to the verifying peer. However, in the scope of VPH-Share project, the data stored on remote cloud resources cannot be altered, as well as no computing element exist on cloud provider site.

As a result, in this thesis we aim to address the above mentioned issues with creation of a service that is periodically monitoring the availability and integrity of data and notifies the owner in case of errors. It was successfully designed, implemented and deployed in production environment of VPH-Share project. However, at this stage of project, DRI is a work in progress and not all of its requirements outlined in VPH-Share deliverable are already met. The core functionality is up and running, but data replication mechanisms are scheduled for the second phase of the project. Nevertheless, this thesis objectives have been evaluated and the results of executing a test scenario were outlined in the chapter devoted to verification and testing.

The summary of the main objectives of this thesis and proposed solutions how they were addressed are presented in table 6.1.

Objective	Proposed solution
Manage data availability and integrity in the cloud	Periodically monitor data integrity status in the cloud
Manage data recovery in the cloud	Provide data replication across cloud storage providers
Efficient data validation in the cloud	Probabilistic data validation algorithm

Table 6.1: Summary of this thesis objectives and proposed solution how to meet them.

6.1. Future work

While working on this thesis, we identified some ideas and tasks that are connected to this work, but were not taken into consideration. However, they could be worth continuation, so we outline them here. We divided them in two groups. The first presents possibilities of enhancements and improvements to this work:

(1) Design and implementation of automatic data replication module. The idea is to take advantage of and combine both data replication and validation. As soon as DRI discovers integrity errors, it will recover from them automatically by restoring the data from other, non-affected replicas. During data recovery, corrupted replica should be excluded from set of replicas available to VPH users.

(2) Investigation and implementation of possible improvements to the validation algorithm. At the time of writing this thesis, cloud storage interfaces are of limited flexibility. Every noncontiguous block of data has to be requested with separate HTTP request. It can significantly affect the efficiency and throughput of validation algorithm. In the current implementation, DRI asynchronously sends a set of HTTP requests to reduce network latency. If cloud providers introduced support for requesting multiple noncontiguous blocks of data in single HTTP call or for emerging SPDY web protocol, it would be beneficial to add support for it in DRI. Another idea it to perform data validation against multiple cloud providers simultaneously. Separate blocks of data should be reqested from different replicas. Other implementation improvements could also be investigated.

(3) Design and investigation how to combine DRI with LOB federated data access (LOBCDER) into one component. LOBCDER provides federated data access for the VPH-Share Cloud Platform – all the requested data flows through this component. Many limitations to DRI design came out from separating these two components by design. In case of ensuring data integrity the combined component could perform data validation on the fly as the data is requested and retrieved from cloud storage. When data corruption occur, it could automatically recover by restoring the data from the remaining replicas. Moreover, it could perform data encryption while storing in the cloud. As a result, validation algorithm would not be constrained with the requirement to store the data in original form, as well as it could be substituted with proofs or retrievability scheme.

The other group addresses the problem of ensuring data integrity in cloud storage in general and abstracts away from VPH-Share project context. The concept monitoring data integrity in DRI service has a potential for being applied as a part of many software solutions. The ideas in this group are the following:

(1) Extract the implementation of data validation mechanism and abstract it away from the context of VPH-Share project. It would be beneficial to take out DRI functionality and share it as open source solution. Needless to say that its architecture should be redesigned and implementation refactored. The design should clearly specify its dependencies and provide a couple of implementations out of the box. Currently, DRI has two core dependencies – metadata registry and notification service. Metadata registry stores all the metadata related to data validation and as such could be implemented as file, database (relational or no-sql) or stored itself on cloud storage in encrypted form. Notification service informs the user about discovered data integrity problems and could be implemented in form of email sender, XMPP protocol bot or sms gateway. Validation algorithm should also be pluggable as different use cases have different requirements and limitations.

(2) Explore new ways of ensuring data integrity in cloud storage or design a new validation algorithm that would satisfy the requirements outlined in this thesis. It is an on-going research in this field as no standards ways of monitoring data integrity in the cloud emerged.

The above future work suggestions provide only a brief description and probably does not exhaust the subject. However, they are provided as an inspiration for the broad spectrum of improvement possibilities.

A. Cracow Grid Workshop 2013 short article

Managing data reliability and integrity in federated cloud storage

Krzysztof Styrc[1], Piotr Nowakowski[1], Marian Bubak[1,2]

[1] ACK CYFRONET AGH , ul. Nawojki 11, 30-950 Kraków, Poland
[2] Department of Computer Science, AGH University of Science and Technology, Kraków, Poland
emails: kstyrc@gmail.com, ymnowako@cyf-kr.edu.pl, bubak@agh.edu.pl

Keywords: data integrity, cloud computing, cloud storage, federated cloud storage

Introduction

Cloud computing is in widespread use nowadays, especially cloud storage which provides virtually unlimited storage capacity and SLA contracts regarding high availability. However recently, numerous cloud provider downtimes and best-effort, return-of-costs SLAs allow to question the reliability of the cloud [1].

In VPH-Share project [2] we aim to build a collaborative computing environment and infrastructure where researchers from the domain of physiopathology of the human body will work together on developing new biomedical simulation software. It is envisioned that the data stored within the platform will be of vast volumes and predominantly of static nature. To avoid the risk of provider unavailability, the data is replicated and stored in federation of public and private cloud storage resources. Additionally, apart from data availability, it is crucially desired to ensure the integrity of the data. Researchers proposed efficient, probabilistic validation schemes such as proofs of retrievability (POR) [3] and data integrity proofs (DIP) [4] which aim to detect data corruption with high probability, while trying to reduce network overhead. However, neither of these methods are directly applicable to VPH-Share, because they (a) require to store the data in encoded and encrypted form, and (b) neglect network latency involved in random-bits access pattern. As a result, we propose a new validation algorithm that aims to provide probabilistic data integrity assurance with regard to VPH-Share, as well as current cloud storage limitations.

Description of a problem solution

In the context of VPH-Share project [2] we propose a data reliability and integrity (DRI) service that provides suitable API to ensure integrity of data in the cloud and to perform data replication across cloud storage providers. DRI periodically checks that the data is available and its content remains in tact. DRI depends on Atmosphere Internal Registry (AIR) for metadata persistence of integrity checksums, datasets and configuration. It accesses multiple cloud storage providers to retrieve VPH-Share data and notifies data owners of detected data unavailability or corruption via Notification Service. Typical use case is as follows: user tags selected dataset for data integrity monitoring, then DRI periodically retrieves dataset metadata from AIR registry, validates the data on multiple cloud storages and notifies the user in case of any problems. Optionally, user can issue dataset validation on request.

Our data validation algorithm modifies the aforementioned DIP approach [4] in two aspects. First, it makes data access patterns less fine grained – we request small blocks of data, not single bits. Second, it stores the integrity metadata in external repository, rather than appending it to the file stored on cloud. In setup phase, our validation algorithm divides

a file *F* into *n* chunks of equal size, computes their MAC-hashes and store them in metadata repository. In validation phase, it randomly selects *k* out of *n* chunks (where $k << n$), computes its hashes again and compares them with the original ones.

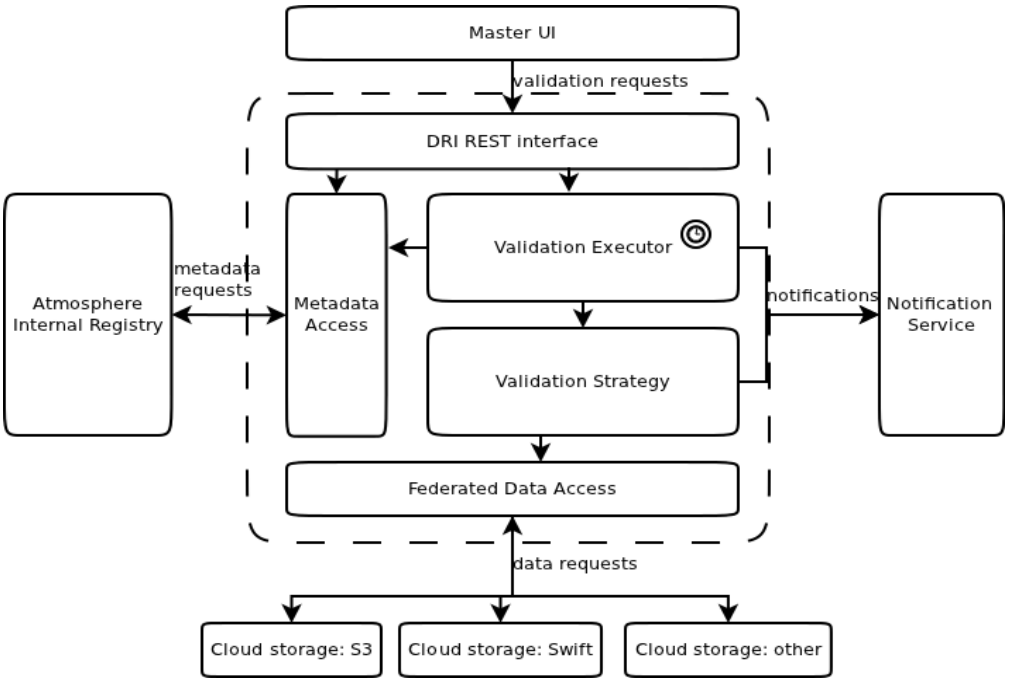


Fig. 1 DRI architecture within VPH-Share environment

Results

In comparison with the approach in which all the content of *F* is fetched, our algorithm significantly reduces network overhead – only *k* out of *n* chunks are downloaded, but provides only probabilistic error detection rate. However, unlike POR and DIP approaches, it (1) separates metadata and data storage and (2) better accommodates to the existing cloud storage API models.

DRI was successfully implemented and deployed within VPH-Share Cloud Platform environment, ensuring users with integrity of their data.

Conclusions and future work

In this work we proposed a method for ensuring data availability and integrity in federated cloud storage and provided a proof of concept DRI component design and its implementation within VPH-Share project.

The future work should focus on (1) investigation of possible improvements of data validation algorithm, as well as (2) separation of DRI service and providing it as a reusable component outside of VPH-Share platform.

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Glossary

Atomic Service (AS) in scope of VPH-Share project it indicates a VM instance on which core application software components have been installed, wrapped as a virtual system image and registered for usage within the platform. Simply a VM with some add-ons.

Blob an unstructured data that is stored in a cloud container. Different cloud storage providers call them objects, blobs or files.

Checksum a value used to verify the integrity of a file or a data transfer. In other words, it is a sum that checks the validity of data. It is typically used to compare two sets of data to make sure they are the same.

Cloud computing a computing paradigm based on virtual infrastructures delivered as hosted services over computer network.

Cloud federation the deployment and management of multiple external and internal cloud computing services to match business needs.

Cloud storage a service model in which data is maintained, managed and backed up remotely and made available to users over a network (typically the Internet).

Data reliability and integrity (DRI) a codename of the tool for ensuring data availability and integrity in federated cloud storage built in scope of this thesis.

Data replication a process of creating exact copies of a set of data from the data site containing the official data source and placing those data in at other data sites. Replication helps to ensure consistency between redundant replicas to improve reliability, fault-tolerance and accessibility.

Dataset a term used in scope of VPH-Share project to simply name a set of files.

Error correcting code (ECC) a system of adding redundant data, or parity data, to a message, such that it can be recovered by a receiver even when a number of errors (up to the capability of the code being used) were introduced, either during the process of transmission or on storage..

Federated cloud storage an integration of diverse cloud storage providers that can avoid limitations associated with relying on single storage provider such as availability, scalability and a vendor lock-in effect.

Java Servlet a Java programming language class that is used to extend the capabilities of servers that host applications accessed by means of a request-response programming model. Although servlets can respond to any type of request, they are commonly used to extend the applications hosted by web servers. For such applications, Java Servlet technology defines HTTP-specific servlet classes..

Message authentication code (MAC) a cryptographic checksum on data to detect both accidental and intentional modifications of the data.

Round-trip time also called round-trip delay, is the time required for a signal pulse or packet to travel from a specific source to a specific destination and back again.

Service Level Agreement a contract between a network service provider and a customer that specifies, usually in measurable terms, what services the network service provider will furnish.

Virtual Machine virtualization technology that enables running operating system instances in isolated environments managed by a hypervisor. Hypervisor performs emulation on hardware resources, and enable multiple Virtual Machines to run simultaneously.

VPH-Share Data and Compute Cloud Platform a platform which goal is to develop and integrate a consistent service-based cloud infrastructure that will enable VPH community to deploy basic components of VPH-Share application workflows on the available computing resources and enact workflows using these services.

Web service a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (WSDL). Other systems interact with the web service in a manner prescribed by its description using messages (SOAP), typically conveyed using HTTP.

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