Performance and Stability of the Chelonia Storage Cloud

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Abstract

In this paper we present the Chelonia storage cloud middleware. It was designed to fill the requirements gap between those of large, sophisticated scientific collaborations which have adopted the grid paradigm for their distributed storage needs, and of corporate business communities which are gravitating towards the cloud paradigm. The similarities to and differences between Chelonia and several well-known grid- and cloud-based storage solutions are commented. The design of Chelonia has been chosen to optimize high reliability and scalability of an integrated system of heterogeneous, geographically dispersed storage sites and the ability to easily expand the system dynamically. The architecture and implementation in term of web-services running inside the Advanced Resource Connector Hosting Environment Dameon (ARC HED) are described. We present results of tests in both local-area and wide-area networks that demonstrate the fault-tolerance, stability and scalability of Chelonia.

Key words: Data Grid, Cloud Storage, Middleware, Distributed Data Management

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1. Introduction

As computationally demanding research areas expand, the need for storage space for results and intermediate data increases. Currently running experiments in areas like high energy physics, atmospheric science and molecular dynamics already generate petabytes of data every year. The increasing number of international and even global scientific collaborations also contributes to the growing need to share (and protect) data efficiently and effortlessly.

While different research groups have different requirements for a storage system, a set of key characteristics can be identified. The storage system needs to be reliable to ensure data integrity. It needs to be scalable and capable to dynamically expand to future needs, and given that many research groups today use computational grids to process their data, it is highly favorable if the storage system is grid-enabled.

Lately, the concept of storage clouds has gone from being completely unknown to being the subject of significant attention from end-users and developers alike [23]. A storage cloud addresses many of the needs mentioned above, but from a user perspective it also hides the complexity of the machinery involved in making the system work. Such a framework requires well-defined roles for the involved parties (the Service Providers and Infrastructure Providers). It also requires these groups to have explicit understandings of and commitments to their roles. Apart from the conceptual agreements, there is a fundamental need for sustainable technology on which the framework can built.

In this paper we will present the design and performance of the Chelonia storage cloud [1, 21]. With Chelonia we aim at designing a system which fulfills the requirements of global research collaborations, but which also meets the specifications of a storage cloud, e.g., user-centric interfaces and transparency. With Chelonia it is possible to build anything from simple storage systems for sharing holiday pictures to large-scale storage systems for storing petabytes of scientific data.

This paper is organized as follows: First we give a brief introduction to distributed data storage solutions in Section 2 before we in Section 3 give an architectural overview of Chelonia and its services. Section 4 exemplifies important features of Chelonia, while Sections 5 and 6 present performance
and stability of Chelonia, respectively. A comparison with other storage solutions on the market is given in Section 7. Section 8 presents ongoing development work, before the conclusions are given in Section 9.

2. Distributed Data Storage Solutions

Over the years, different concepts have evolved to deal with the challenge of handling increasing volumes of data and the fact that the data tend to be generated and accessed over vast geographic regions. The largest storage solutions nowadays can be roughly divided between the data grids developed and used by scientific communities, and cloud storage arising from the needs of corporate business communities. While both concepts have the same goal of distributing large amounts of data across distributed storage facilities, their focuses are slightly different.

Data grid solutions focus on sharing data stored at several large storage facilities which are usually supported by public funding and run by different organizations. A grid storage system provides its clients with access to data stored at remote storage systems. A traditional architecture (see e.g. [15, 12]) typically consists of an indexing service, indexing files from storage resources, a file transfer service for transferring files, a replication service for managing replica locations, and a (often centralized) metadata catalog imposing a global namespace on top of the resources. While they enable the sharing of resources between large number of users, data grids are often considered to be rather cumbersome in use and maintenance. For example, there is no common method of establishing a global namespace and this is achieved only additional effort of the organization that cares for its own data.

Cloud storage focuses more on providing large amounts of storage to other organizations, and one cloud storage facility is usually run by a single organization. The main building blocks of a cloud are the services. The cloud actors access the services both to add resources and utilize resources. The services provides Quality of Service (QoS) guarantees through Service Level Agreements (SLA’s). In clouds, storage is provided through the concept of Data as a Service (DaaS), which together with Infrastructure as a Service (IaaS), Hardware as a Service (HaaS) and Software as a Service (SaaS) can form a Platform as a Service (PaaS). Hence, by combining services, the service user can create a customized virtual platform. While this provides more flexibility for the cloud user and service providers than the grid concept, it limits the ability of sharing resources. When a user has set up a virtual com-
puting platform, this platform is typically limited to be used by this user. Data security is usually realized through isolating the virtual platform to be used only by the one user.

Storage clouds are an emerging paradigm, and even though the focus differs from the data grids, the paradigm has learned from the experience of the grid paradigm and improved on several features like usability and payment plans. However, arising from the needs of corporate business the storage clouds lack features like file-sharing and high-level tools needed by the scientific communities. The Chelonia storage cloud is designed to combine the best of two paradigms for a truly distributed, self-healing, flexible storage solution, with a replicated metadata catalog, easy-to-use storage resources and an operating system-agnostic implementation.

3. Architecture of Chelonia

Chelonia consists of a set of SOAP-based web services residing within the Hosting Environment Daemon (HED) service container from the ARC grid middleware. Together, the services provide a self-healing, reliable, robust, scalable, resilient and consistent data storage system. Data is managed in a hierarchical global namespace with files and subcollections grouped into collections. A dedicated root collection serves as a reference point for accessing the namespace. The hierarchy can then be referenced using Logical Names. The global namespace is accessed the same manner as in local filesystems.

Being based on a service-oriented architecture, the Chelonia storage cloud consists of a set of services as shown in Figure 1. The Bartender (cup) provides the high-level interface to the user; the Librarian (book) handles the entire storage namespace, using the A-Hash (spaceship) as a metadata; and the Shepherd (staff) is the front-end for the physical storage node. Note that any of the services can be deployed in multiple instances for high availability and load balancing. Before going into the technical details of Chelonia itself, it may be beneficial to have a brief look at the middleware providing the communication layer of Chelonia.

\footnote{A concept very similar to files and directories in most common file systems.}
3.1. The Advanced Resource Connector

The Chelonia communication layer is provided by the next generation Advanced Resource Connector (ARC) Grid middleware, developed by NorduGrid [2] and the EU-supported KnowARC project [3]. The next generation ARC is based upon web-services which make frequent use of pluggable components for offering certain capabilities. The ARC services, including Chelonia (Section 3.2), run inside a container called the Hosting Environment Daemon (HED).

There are three basic kinds of pluggable components for HED: Data Management Components (DMC's) are used to transfer the data using various protocols; Message Chain Components (MCC’s) are responsible for the communication within services as well as between the clients and the services; and Policy Decision Components (PDC’s) are responsible for the security model within the system. In Chelonia, the Shepherd uses DMC’s to transfer files, all client-service and inter-service communication goes through the SOAP MCC and the Bartender uses the PDC to decide if a user has access
or not.

3.2. Core Services

The main components of Chelonia are the four services, the A-Hash, the Librarian, the Bartender and the Shepherd. They each have separate roles based on the distinct characteristics of a distributed storage system. When compared with traditional data grid solutions, the Librarian may be viewed as an indexing service and the Shepherd as the manager of the file transfer service. The replication service is provided by the Shepherd, Librarian and Bartender services acting together and the Librarian and A-Hash function as a metadata catalog. When compared with cloud storage solutions, Chelonia provides DaaS with the Bartender providing a well-defined API for easy-to-use access. Acting together, the services provide an easy-to-use, lightweight storage system without single points of failure.

3.2.1. The A-Hash

The A-Hash service is a database that stores objects which contain key-value pairs. In Chelonia, it is used to store the global namespace, all file metadata and information about itself and storage elements. Being such a central part of the storage system, the A-Hash needs to be consistent and fault-tolerant. The A-Hash is replicated using the Oracle Berkeley DB [4] (BDB), an open source database library with a replication API. The replication is based on a single master, multiple clients framework where all clients can read from the database and only the master can write to the database. While a single master ensures that the database is consistent at all times, it raises the problem of having the master as a single point of failure. If the master is unavailable, the database cannot be updated, files and entries cannot be added to Chelonia and file replication will stop working. The possibility of the master failing cannot be completely avoided, so to ensure high availability means must be taken to find a new master if the first master becomes unavailable. BDB uses a variant of the Paxos algorithm [18] to elect a master amongst peer clients: Every database update is assigned an increasing number. In the event of a master going offline, the clients send a request for election, and a new master is elected amongst the clients with the highest numbered database update.

3.2.2. The Librarian

The Librarian service manages the hierarchy and metadata of files and collections, handles the Logical Names and monitors the Shepherd services. The
Librarian service is stateless, instead it stores all the persistent information in the A-Hash. This makes it possible to deploy any number of independent Librarian services to provide high-availability and load-balancing. In this case all the Librarians should communicate with the same set of A-Hashes in order to use the same database of metadata. As only the master A-Hash can be written to and the Librarian cannot know \textit{a priori} which A-Hash replica is the master, the Librarian needs to get this information from one of the A-Hashes. For this reason, the master A-Hash stores the list of all available A-Hashes, so that the information is replicated to all A-Hash replicas. As all A-Hash replicas are readable, the Librarian only needs to know about a few of the A-Hashes at start-up to be able to get this list. During run-time the Librarian holds a local copy of the A-Hash list and refreshes it both regularly and in the case of a failing connection.

3.2.3. The Shepherd

Each instance of the Shepherd service manages a particular storage node and provides a uniform interface for storing and accessing file replicas. On a storage node there must be at least one independent storage element service (with an interface such as HTTP(S), ByteIO, etc.) which performs the actual file transfer. A storage node then consists of a Shepherd service and a storage element service connected together. Storage element services can either be provided by ARC or by third-party services. For each kind of storage element service, a Shepherd backend module is needed to enable the Shepherd service to communicate with the storage element service, e.g., to initiate file uploads, downloads and removal, and to detect whether a file transfer was successful or not. Currently there are three Shepherd backends: One for the ARC native HTTP(S) server called Hopi; one for the Apache web server; and one for a service which implements a subset of the ByteIO interface. In addition to storing files and providing access to them, the Shepherd is responsible for checking if a file replica is valid and, if necessary, initiating replication of the file to other Shepherds.

3.2.4. The Bartender

The Bartender service provides a high-level interface of the storage system for the clients (other services or users). The clients can create and remove collections (directories), create, get and remove files, and move files and collections within the namespace using Logical Names. Access policies associated with files and collections are evaluated by the Bartender (using
the PDC plugin of HED) every time a user wants to access them. The Bartender communicates with the Librarian and Shepherd services to execute the client’s requests. The file content itself does not go through the Bartender; file transfers are directly performed between the storage nodes and the clients.

The Bartender also supports so-called gateway modules which make it possible to communicate with third-party storage solutions, thus enabling the user to access multiple storage systems through a single Bartender client. These modules are protocol-oriented in the sense that external storage managers which support a certain protocol will be handled using the gateway module based on that protocol. While excluding some of the features provided by accessing storage managers directly, this approach reduces the number of gateway modules required for different storage managers. The currently available gateway module is based on the GridFTP protocol[9].

3.3. Security

As is the case for all openly accessible web services, the security model is of crucial importance for the Chelonia storage cloud. While the security of the communication with and within the storage system is realized through HTTPS with standard X.509 authentication, the authorization related security architecture of the storage can be split into three parts; the inter-service authorization; the transfer-level authorization; and the high-level authorization:

- The inter-service authorization maintains the integrity of the internal communication between services. There are several communication paths between the services in the storage system. The Bartenders send requests to the Librarians and the Shepherds, the Shepherds communicate with the Librarians and the Librarians with the A-Hash. If any of these services are compromised or a new rogue service gets inserted in the system, the security of the entire system is compromised. To enable trust between the services, they need to know each other’s Distinguished Names (DN’s). This way a rogue service would need to obtain a certificate with that exact DN from some trusted Certificate Authority (CA).

- The transfer-level authorization handles the authorization in the cases of uploading and downloading files. When a transfer is requested, the
Shepherd will provide a one-time Transfer URL (TURL) to which the client can connect. In the current architecture, this TURL is world-accessible. This may not seem very secure at first. However, provided that the TURL has a very long, unguessable name, that it is transferred to the user in a secure way and that it can only be accessed once before it is deleted, the chance of being compromised is fairly low.

- The high-level authorization considers the access policies for the files and collections in the system. These policies are stored in the A-Hash, in the metadata of the corresponding file or collection, providing a fine-grained security in the system.

### 3.4. Accessing Chelonia

Being the only part a user will (and should) see from a storage system, the client tools are an important part of the Chelonia storage cloud. In addition to a vanilla command-line interface, two ways of accessing Chelonia are supported.

#### 3.4.1. FUSE Module

The FUSE module provides a high-level access to the storage system. Filesystem in Userspace (FUSE) [5] provides a simple library and a kernel-userspace interface. Using FUSE and the ARC Python interface, the FUSE module allows users to mount the storage namespace into the local namespace, enabling the use of graphical file browsers as shown in the screenshot in Figure 2.

#### 3.4.2. Grid Job Access

To access data through the ARC middleware client tools, one needs to go through Data Manager Components (DMC’s). These are protocol-specific plugins to the client tools. For example, to access data from a HTTPS service, the HTTP DMC will be used with a URL starting with `https://`, to access data from an SRM service, the SRM DMC will be used with a URL starting with `srm://`. Similarly, to access Chelonia, the ARC DMC will be used with a URL starting with `arc://`.

The ARC DMC allows grid jobs to access Chelonia directly. As long as A-REX, the job execution service of ARC, and ARC DMC are installed on a site, files can be both downloaded and uploaded by specifying the corresponding URL’s in the job description. In this case, the Bartender URL needs to
be embedded in the URL as a URL option. For example, if a job requires an input file `/user/me/input.dat`, the URL specified in the job description will be as follows (given that the file can be found by a Bartender with URL `https://storage/Bartender`):

```
arc:///user/me/input.dat?BartenderURL=https://storage/Bartender
```

4. Chelonia in Operation

Both the Chelonia storage system and its clients can be installed from binary packages (available for several different platforms) or after compiling the source packages. A fully operational storage cloud requires a minimum installation of one instance of every service described above. The Chelonia Administrator manual [19] gives detailed instructions on how to install, configure and run the services. In order for users to interact with Chelonia, several user tools are provided. These are documented both in the Chelonia user manual [20] and Linux man pages and directly through command line calls.
For the user, transferring files to and from Chelonia are simple operations. For example, if a user wants to upload a file `orange.jpg` to Chelonia, he/she can use, e.g., the Chelonia CLI. Assuming that the URL of one or more Bartenders and the required number of file replicas are written in a configuration file, the user gives the command

```plaintext
chelonia put orange.jpg /user/me/orange.jpg
```

Note that there is no need for the user to know where files are physically stored or will be stored in Chelonia.

Under the hood of Chelonia, the Bartender receiving the request from the CLI contacts a Librarian to create an entry in the Chelonia namespace. If the Librarian confirms the new entry, the Bartender then contacts a Shepherd to get a transfer URL which is returned to the CLI. When the CLI has uploaded the file, the Shepherd queries the Librarian to find out how many replicas are needed and, if needed, initiates a file transfer to another Shepherd. In the case of downloading a file, the Bartender gets the locations of the file from a Librarian, chooses one of them and contacts the corresponding Shepherd for a transfer URL.

When in operation, the Chelonia storage cloud is a pulsing system where heartbeats are periodically sent from each Shepherd to a Librarian together with information about replicas whose state changed since the last heartbeat. Heartbeats are stored in the A-Hash, thus making them visible to all Librarians in the system. If any of the Librarians notices that a Shepherd is late with its heartbeat, it will mark all the replicas in that Shepherd as offline.

In addition to the heartbeat, the Shepherds periodically check with the Librarians to see if there are sufficient replicas of the files in Chelonia and if the checksums of the replicas are correct. If a file is found to have too few replicas, the Shepherd informs a Bartender about this situation and together they ensure that a new replica is created at a different storage node. A file having too many replicas will also be automatically corrected by Chelonia - the first Shepherd to notice this will mark its replica(s) as unneeded and later delete it (them). Replicas with invalid checksums are marked as invalid, and as soon as possible replaced with a valid replica.

With the Chelonia gateway module, a user can mount external storage systems into the Chelonia namespace. For example, if a Chelonia user has access to a set of files stored in dCache [16] (see Section 7) under `/fruits` he
can add a mount point (say /my/dCache) to easily access these data through the Chelonia namespace, i.e., using standard Chelonia commands like

```
chelonia get /my/dCache/fruits/apple.jpg
```

More technically, when the Bartender looks up the entry /my/dCache which is a mount point to dCache, it will use the corresponding gateway module to generate an external URL which the client tool will use to contact dCache directly. This way, Chelonia can include third-party storage namespaces in its global namespace by simply storing a single entry.

5. System Performance

5.1. Adding and Querying the Status of Files

In a hierarchical file system files are stored in levels of collections and sub-collections. The time to add or get a file depends mainly on two factors; the number of entries in the collection where the file is inserted, and the number of parent collections to the collection where the file is inserted (the depth of the collection). Based on these two factors we have run two different tests:

- **Depth test** tests the performance when creating many levels of sub-collections. The test adds a number of sub-collections to a collection, measures the time to add and stat the sub-collections, then adds a number of sub-sub-collections to one of the sub-collections and so forth. To query a collection at a given level means that all the collections at the lower levels needs to be queried first. In Chelonia, each query causes a message to be sent through TCP. Hence, it is expected that time will increase linearly as the level of collections increases. As every message is of equal size, this test ideally depends only on network latency.

- **Width test** tests the performance when adding many entries (collections) to one collection. The test is carried out by adding a given number of entries to a collection and measuring the time to add each entry and the time to stat the created entry. When adding an entry to a collection, the system needs to check first if the entry exists. In Chelonia, this means that the list of entries in the collection needs to be transferred through TCP. It is therefore expected that the time to add an entry will increase linearly as this list increases and ideally the time will depend only on the bandwidth of the network.
Both tests were run in two types of environments: In the Local Area Network (LAN) setup four computers were connected to the same switch. A centralized A-Hash service, a Librarian, a Bartender, and the client were each run on a separate computer. In the Wide Area Network (WAN) setup, the client and Bartender were located in Uppsala, Sweden, while the Librarian and a replicated A-Hash consisting of three replicas were located in Oslo, Norway.

The test result for the depth test is shown in Figures 3(a) (LAN) and 3(b) (WAN). The continuous lines show the time to create an entry, while the dashed lines show the time to get the status of the collection. All the plots are averages of five samples, with the error bars representing the minimum and maximum values. The LAN test shows a near-perfect linear behaviour, with the error bars too small to be seen. As mentioned earlier, since the packet size for each message is constant in this test, the main bottleneck (apart from Chelonia itself) is the network latency. Since all computers in the LAN test are connected to the same switch we can assume that the latency is near constant. Hence, the LAN test shows that in a very simple network scenario Chelonia works as expected, with the network being the major bottleneck. Notice also that creating an entry consistently takes 0.021 s longer than getting the status of the collection, again corresponding to the extra message needed to create an entry.

In the WAN test, the complexity is a bit increased, as in addition to sending messages over WAN, the A-Hash is now replicated. The time still increases linearly, albeit with more fluctuation due to the WAN environment.
Creating an entry at the first level in the hierarchy now takes 0.11 s longer than getting the status of the collection, corresponding to the fact that the entry needs to be replicated three times. However, at higher levels, getting the status over WAN is actually faster than getting the status over LAN. The effect of the replicated A-Hash will be discussed in more detail in Section 5.4.

The test results for the width test are shown in Figures 4(a) (LAN) and 4(b) (WAN). The continous lines show the time to add entries to a collection and the dotted lines show the time to get the status of a collection containing the given number of entries. The operations were repeated five times, with the plots showing the averages of these five samples. As expected, the time increase linearily with increasing number of entries. The results of the WAN test fluctuate more than those of the LAN test, which is to be expected; in the LAN test all services are on computers connected to the same switch, while in the WAN test, the services are distributed between two different countries. However, the WAN test shows similar linearity, albeit with a slightly higher response time. It is worth noticing that for the width test, in contrast to the depth test, we see no benefit of using a replicated A-Hash. This is due to the fact that the bandwith is the limiting factor in this test.

An interesting feature of both tests is that while creating an entry takes more time when there are only few entries in the collection, creating new entries is actually faster than stating the collection when the collection has many entries. This is due to the fact that getting the status of a collection requires the metadata of the collection (and hence the list of entries in the collection) to be transfered first from the A-Hash to the Librarian, and second
from the Librarian to the Bartender and last from the Bartender to the client. When creating an entry, neither the Bartender nor the client needs this list of entries, so that less data is transferred between services. However, for fewer entries, creating new entries is more expensive since the Bartender needs to query the Librarian twice, first to check if it is allowed to add the entry and second to actually add it.

5.2. File Replication

The concept of automatic file replication in Chelonia was presented in Section 4. In this section we will demonstrate both how Chelonia works with different file states to ensure that a file always has the requested number of valid (ok) replicas and how Chelonia distributes the replicas in the system in order to ensure maximum fault tolerance of the system.

The test system consists of one Bartender, one Librarian, two A-Hashes (one client and one master) and five Shepherds. All services are deployed within the same LAN. As a starting point 10 files of 114 MB are uploaded to the system and for each file 4 replicas are requested. Thus the initial setup of the test system contains 40 replicas with an initial distribution of file replicas as shown in Table 1.

| Shepherd | Initial | Final |
|----------|---------|-------|
| S1       | 9       | 9     |
| S2       | 8       | 7     |
| S3       | 8       | 8     |
| S4       | 7       | 9     |
| S5       | 8       | 7     |
| **Total**| **40**  | **40**|

Table 1: Initial and final load distribution of 40 files on 5 Shepherds

The first phase of the file replication test was to kill one of the Shepherd services, S3, of the test system. Chelonia soon recognized the loss of this service (no heartbeat received within one cycle) and started compensating for the lost replicas. File replicas in Chelonia have states ALIVE, OFFLINE, THIRDWHEEL or CREATING which are recorded in the A-Hash. Initially the test system had 40 ALIVE replicas (10 files with 4 replicas each), but when the Librarian did not get the S3 heartbeat it changed the state of the 8 replicas stored in S3 to OFFLINE.
At this point a number of files stored in our Chelonia setup had too few ALIVE replicas. As explained above, the Shepherds check periodically that files with replicas stored on its storage element have the correct number of ALIVE replicas. Thus, in the next cycle the S1, S2, S4 and S5 Shepherds started to create new file replicas which initially appeared in the system with the state CREATING.

Figure 5 gives a graphical overview of the number of replicas and the replica states in the test system every 15 seconds. At 15 s (00:15) all 40 file replicas were ALIVE as explained above, but soon thereafter S3 was turned off and the other Shepherds started creating new replicas. Queried at 30 s (00:30) the system contained 32 ALIVE, 8 OFFLINE and 1 CREATING file replica.

While the system worked on compensating for the loss of S3, the second phase of the replication test was initiated by turning the S3 shepherd online again. The reappearance of the S3 Shepherd can be seen in Figure 5 at 90s (01:30) as a significant increase in the number of ALIVE replicas. In fact there were now too many ALIVE replicas in the system and at 105 s (01:45) 2 replicas were marked as THIRDWHEEL (the Chelonia state for redundant replicas). THIRDWHEEL replicas are removed from Chelonia as soon as possible, and during the next 45 s the system removed all such replicas. A query of the system at 165 s (02:45) shows that the system once again contained 40 ALIVE replicas. The final distribution of replicas between Shepherds is given in Table 1.

5.3. Multi-User Performance

While any distributed storage solution must be robust in terms of multi-user performance, it is particularly important for a grid-enabled storage cloud like Chelonia where hundreds of grid jobs and interactive users are likely to interact with the storage system in parallel. To analyze the performance of Chelonia in such environments we have studied the response time of the system while increasing the number of simultaneous users (multi-client).

Due to limited hardware resources, multiple clients for the tests were simulated by running multiple threads from three different computers. Each client thread creates 50 collections sequentially and tests were done for an increasing number of simultaneous clients. For each test the minimum, average and maximum time used by the client was recorded. Figure 5.3 shows the system response times for up to 100 simultaneous clients using the above-
Figure 5: Number of replicas and their corresponding states when querying the test system every 15 seconds. Shepherd S3 is turned offline between 00:15 and 00:30 and back online between 01:15 and 01:30.

mentioned testbed deployment. The shown test was run in a LAN environment with one centralized A-Hash, one Librarian and one Bartender.

The test results show that the response time of the system increases linearly with an increasing number of simultaneous clients. From 40 clients and onwards the difference between the fastest client and slowest client starts to become sizeable. When running 50 clients or more in parallel, it was occasionally observed that a client’s request failed due to the heavy load of the system. When this happened, the request was retried until successfully completed, as shown by the slightly fluctuating slope of the mean curve. The same linearity was seen in the corresponding WAN test (not shown), albeit with a factor two higher average time, consistent with the results observed in the depth and width tests in Section 5.1.

As can be noted in Figure 5.3, for more than 30 clients, the maximum times increase approximately linearly while the minimum times are close to constant. The reason for this is a limitation on the number of concurrent threads in the Hosting Environment Daemon (HED). If the number of concurrent requests to HED reaches the threshold limit, the requests are queued so that only a given number of requests are processed at the same time. In the test each client used only one connection for creating all 50 collections. Hence, the fastest request was one that had not been queued so that when
the number of requests was above the threshold, the minimum timing did not depend on the total number of clients. On the other hand, the slowest request was queued behind several other requests so that the maximum time increased with the number of simultaneous clients.

5.4. Centralized and Replicated A-Hash

As the A-Hash stores all metadata about files, file locations and shepherds, it is important that the A-Hash is fault tolerant and able to survive even fatal hardware failures. While in theory replicating the A-Hash provides these features, the replication adds complexity to the A-Hash in that all data need to be replicated to all A-Hash instances. Additionally, in the event of a failing A-Hash instance, the Librarians need to seamlessly find and connect to other A-Hashes.

To test the fault tolerance and performance overhead of the replicated A-Hash in a controlled environment, four tests have been set up with services and a client on different computers in the same LAN:

1. **Centralized**: One client contacting a centralized A-Hash was set up as a benchmark, as this is the simplest possible scenario.
2. **Replicated, stable**: One client contacting three A-Hash instances (one A-Hash master, two A-Hash clients) randomly. All the A-Hashes were running during the entire test.

3. **Replicated, unstable clients**: Same setup as in point 2, but with a random A-Hash client restarted every 60 seconds.

4. **Replicated, unstable master**: Same setup as in point 2, but with the master A-Hash restarted every 60 seconds.

While setups 1 and 2 test the differences in having a centralized A-Hash and a replicated A-Hash, setups 3 and 4 tests how the system responds to an unstable environment. In all four setups the system has services available for reading at all times. However, in setup 3 one may need to reestablish connection with an A-Hash client and in setup 4 the system is not available for writing during the election of a new master. During the test the client computer constantly and repeatedly contacted the A-Hash for either writing or reading for 10 minutes. During write tests the client computer reads the newly written entry to ensure it is correctly written.

| Reading                      | Minimum (s) | Average (s) | Maximum (s) |
|------------------------------|-------------|-------------|-------------|
| Centralized                  | 0.003399    | 0.003780    | 0.013441    |
| Replicated, stable           | 0.003453    | 0.003738    | 0.013261    |
| Replicated, unstable clients | 0.003412    | 0.003754    | 0.289535    |
| Replicated, unstable master  | 0.003402    | 0.003763    | 1.971131    |

| Writing                      | Minimum (s) | Average (s) | Maximum (s) |
|------------------------------|-------------|-------------|-------------|
| Centralized                  | 0.003828    | 0.004260    | 0.014459    |
| Replicated, stable           | 0.016866    | 0.033902    | 1.057602    |
| Replicated, unstable clients | 0.016434    | 0.034239    | 1.131142    |
| Replicated, unstable master  | 0.016293    | 0.044586    | 60.902862   |

Table 2: Timings for reading from and writing to a centralized A-Hash compared with a stable replicated A-Hash, a replicated A-Hash where clients are restarted and a replicated A-Hash where the master is restarted.

Table 2 shows timings of reading from and writing to the A-Hash for the four setups. As can be seen, for reading, all four setups have approximately the same performance. Somewhat surprisingly, the replicated setups actually perform better than the centralized setup, even though only one client computer was used for reading. While reading from more A-Hash instances is an
advantage for load balancing in a multi-client scenario, one client computer can only read from one A-Hash instance at a time. Thus, the only difference between the centralized and replicated setups in terms of reading is how entries are looked up internally in each A-Hash instance, where the centralized A-Hash uses a simple Python dictionary, while the replicated A-Hash uses the Berkeley DB which has more advanced handling of cache and memory.

Looking at the write performance in Table 2, there is a more notable difference between the centralized and the replicated setups. On average, writing to the replicated A-Hash takes almost 10 times as long as writing to the centralized A-Hash. The reason for this is that the master A-Hash will not acknowledge that the entry is written until all the A-Hash instances have confirmed that they have written the entry. While this is rather time-consuming, it is more important that the A-Hash is consistent than fast. It is however worth noticing when implementing services using the A-Hash, that reading from a replicated A-Hash is much faster than writing to it.

6. System Stability

While optimal system performance may be good for the day-to-day user experience, the long-term stability of the storage system is an absolute requirement. It does not help to have a response time of a few milliseconds under optimal conditions if the services need to be frequently restarted due to memory leaks or if the servers become unresponsive due to heavy load.

To test the system stability, a Chelonia deployment was run continuously over a week’s time. During the test a client regularly interacted with the system, uploading and deleting files and listing collections. The deployment consisted of one Bartender, one Librarian, three A-Hashes and two storage nodes, each consisting of a Shepherd and a Hopi service. All the services and the client ran on separate servers in a LAN environment.

Figure 7 shows the overall memory utilization for seven of the services for the entire run time (top), the A-Hashes and the Librarian in the first 24 hours (bottom left) and the Librarian, the Bartender and one of the Shepherds in the last 37 hours (bottom right). The memory usage was measured by reading the memory usage of each service process in 5 seconds intervals using the Linux ps command.

The most crucial part of Chelonia, when it comes to handling server failures, is the replicated A-Hash. If the A-Hash becomes unavailable, the entire system is unavailable. If a client A-Hash goes down, the Librarians
Figure 7: Resident memory utilization of the Chelonia services during an 8 day run.
may need to find a new client. If the master A-Hash goes down, the entire system will be unavailable until a new master is elected. The bottom left of Figure 7 shows the memory consumption of the three A-Hashes, A-Hash2, A-Hash3 and A-Hash7, and the Librarian during the first 24 hours of the stability test. When the test started A-Hash3 (red line) was elected as A-Hash master, and the Librarian started using A-Hash7 (blue line) for read operations. After 2.5 hours, A-Hash3 was stopped (seen by the sudden drop of the red line), thus forcing the two remaining A-Hashes to elect a new master between them. While not visible on the figure, the A-Hash, and hence Chelonia, was unavailable for a 10 seconds period during the election, which incidentally was won by A-Hash2 (black line). After three additional hours, A-Hash3 was restarted, thus causing an increase of memory usage for the master A-Hash as it needed to update A-Hash3 with the latest changes in the database. Eight hours into the test, the same restart procedure was carried out on A-Hash7 which was connected to the Librarian. This time there was no noticeable change in performance. However A-Hash3 increased memory usage when the Librarian connected to it.

The bottom right of Figure 7 shows the memory usage of the Bartender, the Librarian and one of the shepherds in the last 37 hours of the test. Perhaps most noteworthy is that the memory usage is very stable. The main reason for this is due to the way Python, the programming language of Chelonia, allocates memory. As memory allocation is an expensive procedure, Python tends to allocate slightly more memory than needed and avoids releasing the already acquired memory. As a result, the memory utilization gets evened out after a period of time even though the usage of the system varies. During the run-time of the test, files of different sizes were periodically uploaded to and deleted from the system. The slight jump in memory usage for the Bartender (green line) was during an extraordinary upload of a set of large files. This jump was followed by an increase in memory for the Librarian when the files were starting to be replicated between the Shepherds, thus causing extra requests to the Librarian.

Figure 8 shows the CPU load for six of the services. While the load on the A-Hashes, the Bartender and the Librarian are all below 2.5% of the CPU, Shepherd-1 (bottom left) and Shepherd-8 (bottom right) use around 10% and 20%, respectively. While the difference between the Shepherds is due to the fact that Shepherd-1 was run on a server with twice the number of CPU's as the server of Shepherd-8, the difference between the Shepherds and the other services is due to the usage pattern during the test. To confirm that
Figure 8: CPU load of the Chelonia services during an 8 day run. Each point is an average of the CPU usage of the previous 60 seconds.
the files stored on the storage node are healthy, the Shepherd calculates a checksum for each file, first when the file is received and later periodically. In periods where no new files are uploaded, the Shepherds use almost no CPU as already stored files don’t need frequent checksum calculations. However, when files are frequently uploaded, deleted and re-uploaded, as was the case during the test, the number of checksum calculations, and hence the CPU load, increases significantly. This can particularly be seen on January 1 and 4 when a set of extra large files were uploaded, causing spikes in the CPU load of the two Shepherds. Note also that the spikes occurs at the same time for both Shepherd, as should be expected in a load balanced system.

7. Related Work

There are a number of grid and cloud storage solutions on the market, focused on different storage needs. While direct performance comparison with Chelonia is beyond the scope of this paper, some similarities and differences between Chelonia and related storage solutions are worth mentioning.

In the cloud storage family, Amazon Simple Storage Service (S3) promises unlimited storage and high availability. Amazon uses a two-level namespace as opposed to the hierarchical namespace of Chelonia. In the security model of S3, users have to implicitly trust S3 entirely, whereas in Chelonia users and services need to trust a common independent third party Certificate Authority. Additionally, S3 lacks fine-grained delegation and access control lists are limited to 100 principals, limiting the usability for larger scientific communities.

While Chelonia is designed for geographically distributed users and data storage, Hadoop with its file system HDFS is directed towards physically closely-grouped clusters. HDFS builds on the master-slave architecture where a single NameNode works as a master and is responsible for the metadata whereas DataNodes are used to store the actual data. Though similar to Chelonia’s metadata service, the NameNode cannot be replicated and may become a bottleneck in the system. Additionally, HDFS uses non-standard protocols for communication and security while Chelonia uses standard protocols like HTTP(S), GridFTP and X509.

When compared to typical grid distributed data management solutions, the closest resemblance with Chelonia is the combination of the storage el-
element Disk Pool Manager (DPM) and the file catalog LCG\textsuperscript{2} File Catalog (LFC) \cite{17}. By registering all files uploaded to different DPM’s in LFC one can achieve a single uniform namespace similar to the namespace of Chelonia. However, where Chelonia has a strong coupling between the Bartenders, Librarians and Shepherds to maintain a consistent namespace, DPM and LFC have no coupling such that registration and replication of files is handled on the client side. If a file is removed or altered in DPM, this may not be reflected in LFC. In Chelonia, a change of a file has to be registered through the Bartender and propagated to the Librarian before it is uploaded to the Shepherd.

dCache \cite{16} differs from Chelonia in that dCache has a centralized set of core services while Chelonia is distributed by design. dCache is a service-oriented storage system which combines heterogeneous storage elements to collect several hundreds of terabytes in a single namespace. Originally designed to work on a local area network, dCache has proven to be useful also in a grid environment, with the Nordic Data Grid Facility (NDGF) dCache installation \cite{10} as the largest example. There, the core components, such as the metadata catalogue, indexing service and protocol doors are run in a centralized manner, while the storage pools are distributed. Chelonia, designed to have multiple instances of all services running in a grid environment, will not need a centralized set of core services. Additionally, dCache is relatively difficult to deploy and integrate with new applications. Being a more lightweight and flexible storage solution, Chelonia aims more towards new, less demanding, user groups which are generally less familiar with grid solutions.

Scalla \cite{11} differs from Chelonia in that Scalla is designed for use on centralized clusters, while Chelonia is designed for a distributed environment. Scalla is a widely used software suite consisting of an xrootd server for data access and an olbd server for building scalable xrootd clusters. Originally developed for use with the physics analysis tool ROOT \cite{13}, xrootd offers data access both through the specialized xroot protocol and through other third-party protocols. The combination of the xrootd and olbd components offers a cluster storage system designed for low latency, high bandwidth environments. In contrast, Chelonia is optimized for reliability, consistency and scalability at some cost of latency and is more suitable for the grid environment where wide area network latency can be expected to be high.

\textsuperscript{2}LHC (Large Hadron Collider) Computing Grid
Unlike Chelonia, iRODS \[8\] does not provide any storage itself but is more an interface to other, third-party storage systems. Based on the client-server model, iRODS provides a flexible data grid management system. It allows uniform access to heterogeneous storage resources over a wide area network. Its functionality, with a uniform namespace for several Data Grid Managers and file systems, is quite similar to the functionality offered by our gateway module. However, iRODS uses a database system for maintaining the attributes and states of data and operations. This is not needed with Chelonia’s gateway modules.

8. Future Work

In addition to the continuous process of improvements and code-hardening (based on user feedback) there are plans to add some new features.

The security of the current one-time URL based file transfers could be improved by adding to the URL a signed hash of the IP and the DN of the user. In this way the file transfer service could do additional authorization, allowing the file transfer only for the same user with the same IP.

Because of the highly modular architecture of both Chelonia and the ARC HED hosting environment, the means of communication between the services could be changed with a small effort. This would enable less secure but more efficient protocols to replace HTTPS/SOAP when Chelonia is deployed inside a firewall. This modularity also allows additional interfaces to Chelonia to be implemented easily. For example, an implementation of the WebDAV protocol would make the system accessible to standard clients built into the mainstream operating systems.

Another possible direction for enhancing the functionality of Chelonia is to add handling of SQL databases. In addition to files, the system could store database objects and use databases as storage nodes to store them. SQL databases allow running extensive queries to get the desired information. In a distributed environment, high availability and consistency is often ensured by the replication of data. Access to multiple copies of the data in the system also allows queries to be run in parallel. Consistent, multiple copies of the data also provides a simple, transparent platform for scalable access to the same data to a large number of distributed clients.
9. Conclusions

Chelonia is a cloud-like storage solution with grid capabilities. While its core services resembles those of a traditional data grid, the single-entry interface and the capabilities resemble those of storage clouds.

An important part of developing a distributed storage system is proper testing of the system, both in terms of performance and stability. The presented tests are designed to give an understanding of how Chelonia behaves in a real-life environment while at the same time controlling the environment enough to get interpretable results. The tests have shown that Chelonia can handle both deep and wide hierarchies as expected, both in LAN environments and in WAN environments. The system has shown self-healing capabilities, both in terms of individual service stops and in terms of file availability. Multiple clients have accessed the system simultaneously with reasonable performance results and, even more importantly, Chelonia has been heavily used for more than a week with stable performance even with vital services being shut down during the test.

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