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Replication and Caching Systems for the support of VMs stored in File Systems with Snapshots

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ABSTRACT

Recently, in a relatively short timeframe, there were fundamental changes in the way computing power is used. Virtualisation technology has changed both the model of a data centre's infrastructure and the way physical computers are now managed. This shift is a consequence of today's fast deployment rate of Virtual Machines (VM) in a high consolidation environment with minimal need for human management.

New approaches to virtualisation techniques are being developed at a surprisingly fast rate, leading to a new exciting and vibrating ecosystem of platforms and services. We see the big industry players tackling problems such as *Desktop Virtualisation* with moderate success, but completely ignoring the computation power already present in their clients' infrastructures and, instead, opting for a costly solution based on powerful new machines. There's still room for improvement in Virtual Desktop Infrastructure (VDI) and development of new architectures that take advantage of the computation power available at the user's desk, with a minimum effort on the management side; Infrastructure for Client-Based Desktops (iCBD) is one of these projects.

This thesis focuses on the development of mechanisms for the replication and caching of VM images stored in a local filesystem, albeit one with the ability to perform snapshots. In this work, there are some challenges to address: the proposed architecture must be entirely distributed and completely integrated with the already existing client-based VDI platform; and it must be able to efficiently cope with very large, read-only files, (some of them snapshots) and handle their multiple versions. This work will also explore the challenges and advantages of deploying such a system in a high throughput network, with both high availability and scalability while efficiently supporting a large number of users (and their workstations).

Keywords: VDI, Btrfs File System, Snapshots, Replication Middleware, Cache Servers.

RESUMO

Nos últimos anos tem-se assistido a mudanças fundamentais na forma como a capacidade computacional é utilizada - com o grande aumento da utilização da virtualização, tanto a forma como são geridas as máquinas físicas como os modelos de infraestruturas num centro de dados sofreram grandes alterações. Estas mudanças são o resultado da procura por uma forma de disponibilizar rapidamente VMs num ambiente altamente consolidado e com necessidades mínimas de intervenção humana na sua gestão.

Estão a ser desenvolvidas novas abordagens às técnicas de virtualização a um ritmo nunca visto, o que leva à existência de um ecossistema altamente volátil com novas plataformas e serviços a serem criados a todo o momento. É possível apreciar o esforço de grandes empresas da indústria das tecnologias de informação relativamente a problemas como a virtualização de desktops - com algum sucesso, mas ignorando completamente o poder de computação que está presente nos Personal Computers (PCs) instalados, optando por uma via de custo elevado, baseada em máquinas poderosas. Existe ainda espaço para melhores soluções e para o desenvolvimento de tecnologias que façam uso das capacidades de computação que já se encontram presentes nas organizações, mantendo a simplicidade da sua configuração.

Esta tese foca-se no desenvolvimento de mecanismos de replicação e *caching* para imagens de máquinas virtuais armazenadas num sistema de ficheiros local que tem a funcionalidade (pouco habitual) de suportar *snapshots*. A arquitectura da solução proposta tem de ser distribuída e integrar-se na solução *client-based VDI* já desenvolvida no projecto iCBD; tem de suportar eficientemente ficheiros com vários GB (alguns deles resultantes da criação de *snapshots*) acedidos em leitura, e manter destes múltiplas versões. A solução desenvolvida tem ainda de oferecer desempenho, alta disponibilidade, e escalabilidade na presença de elevado número de clientes geograficamente distribuídos.

Palavras-chave: VDI, Sistema de Ficheiros Btrfs, Snapshots, Middleware de Replicação, Servidor de Caching.

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ACRONYMS

API Application Programming Interface.

BIOS Basic Input/Output System.

CLI Command Line Interface.

CoW Copy-on-Write.

CPU Central Processing Unit.

DaaS Desktop as a Service.

DC Data Centre.

DHCP Dynamic Host Configuration Protocol.

FAT File Allocation Table.

FS File System.

HTTP Hypertext Transfer Protocol.

IaaS Infrastructure as a Service.

iCBD Infrastructure for Client-Based Desktop.

iMI iCBD Machine Image.

IP Internet Protocol.

iSCSI Internet Small Computer Systems Interface.

IT Information Technology.

KVM Kernel-based Virtual Machine.

LAN Local Area Network.

NFS Network File System.

NTFS New Technology File System.

ACRONYMS

NVRAM Non-Volatile Random-Access Memory.

OS Operating System.

PC Personal Computer.

PXE Preboot Execution Environment.

RAID Redundant Array of Independent Disks.

RAM Random-Access Memory.

RCS Replication and Caching Service.

RDP Remote Desktop Protocol.

RDS Remote Desktop Services.

REST Representational State Transfer.

RFB Remote Framebuffer Protocol.

RPC Remote Procedure Call.

SSH Secure Shell.

TCP Transmission Control Protocol.

TFTP Trivial File Transfer Protocol.

UDP User Datagram Protocol.

VDI Virtual Desktop Infrastructure.

VLAN Virtual Local Area Network.

VM Virtual Machine.

VMM Virtual Machine Monitor.

INTRODUCTION

1.1 Context

The concept of virtualisation, despite all the recent discussion and hype, isn't new: the technology has been around since the 1960s [11], but it was not until it was available for the x86 architecture [2] and, later on, further developed with the introduction of Intel VT [47] and AMD SVM [24] in the 2000s, that virtualisation has entered the mainstream as a must-have technology for server deployment across any production environments.

With efficient techniques that take advantage of all available resources, and continuously lowering price points on hardware, an opportunity for the advance in application architecture and a revamp in the supporting infrastructure was at hand.

However, companies realised that the cost to run an in-house, fully fledged data centre (DC) may be, in some cases, unreasonable, and that building and managing it is also a cumbersome task. And, cost is high - not as a consequence of hardware costs, but when factoring in all other parcels: cooling systems that extract the heat generated by servers, storage and networking, physical security to protect the DC, fire suppressing systems and, the largest factor, cost of manpower to maintain the infrastructure; when all these parcels are added together, the result is a high value for OPEX (operational expenditures).

To further aggravate costs, demand for instantaneous access to information coupled with an ever-increasing amount of data to handle also demands a level of resources that continues to grow every day.

This created an opportunity for the Infrastructure as a Service (IaaS) [38] cloud model that, in the case of public clouds, outsources all the resource provisioning to third parties, which are (must be) experts in maintaining very large data centres, geographically dispersed across the globe (for high availability), and can benefit from high discounts from suppliers (hardware, energy, etc.).

With major industry players building their own, very large DCs, and offering both public and hybrid cloud services, supporting more and more types of services with an increasing number of customers, new ways to store data have emerged, and distributed object storage is the platform that supports other storage paradigms – files, databases, key-value stores, etc. – that exhibit high degrees of reliability, consistency, performance, scalability, all essential to a broad range of applications with different workloads.

But, as always, there's no one size fits all solution, and clouds are no exception: some environments have peculiarities – such as low latency, and the cost to keep it under control – that dictates that computing resources must be close to the user; one of these environments is Desktop Virtualisation. VDIs, i.e., Virtual Desktop Infrastructures, are computing infrastructures that provide their users with a virtual desktop: when the user picks his/her workstation (usually PC or laptop) and interacts with it, the desktop application (e.g., Windows Desktop, CentOS Gnome, Ubuntu Unity) displayed at the device's screen is not running natively on the user's workstation. It is running in a Virtual Machine (VM).

This is the umbrella (context) of our thesis/project: an infrastructure that runs VMs that act as the user's "personal computer" and that he/she can access anywhere where a network is available (subject, naturally, to security and performance constraints), using another computer for that task. The remainder of this chapter will provide more details but, for now, we want to add that previous work was researched and developed a VDI, named iCBD, that is running and functionally "complete". Our task is to provide features that will bring fault-tolerance, high-availability and scalability to the solution (with an eye on cost).

1.2 Motivation

Virtualisation is the pillar technology that enabled the widespread availability of IaaS cloud providers, benefiting of economies of scale. These cloud providers, such as Amazon AWS [7], Microsoft Azure [39] and Google Cloud Platform [20], manage thousands of physical machines all over the globe, with the vast majority of their infrastructures being multi-tenant oriented.

The sheer magnitude of those numbers leads to an obvious problem, i.e., how to store all this data efficiently. And, not only there is the need to store customer's generated data but also to manage all the demands of the infrastructure and the multitude of services offered. One approach taken by these companies was the development of their proprietary storage solutions. For instance, Google uses BigTable distributed storage system [12], to store application-specific data, and then serve it to users. This system relies on the Google File System underneath to provide a robust solution to store logs and data files and was designed to be reliable, scalable and fault tolerant.

One characteristic in particular that stands out and is present in many of today's very large storage infrastructures is the use of snapshots with copy-on-write (CoW) techniques.

The adoption of such mechanisms allows for quick copy operations (a.k.a. cloning) of large data sets while saving resources and, at the same time, providing transparent concurrent operations as read-only versions of the data always are always ready for use – e.g., to perform backups - while applications simultaneously execute write operations on their snapshots. But large storage infrastructures are distributed; hence, the other important mechanisms are replication, and data distribution: the duplication of records across multiple machines, serves not only as a “security net”, in case of a fault (as duplication removes the single point-of-failure characteristic), but can also be used to take advantage of network bandwidth (as one can spread a single access across multiple servers, i.e., accessing several “duplicate segments”).

While the above discussion was focused on distributed storage systems, some of these features, namely snapshots, are also available in non-distributed file storage implementations. One of these recently developed systems that has a significant adoption in the Linux community is Btrfs [48].

Btrfs, whose name derives from B-tree data structures, was designed with two goals: support snapshots and maintain excellent performance in a comprehensive set of conditions. We, bounded by the iCBD’s project goals, claim that the combination of Btrfs with replication and partitioning techniques opens up the way to a more advanced solution that serves the needs of an up-to-date storage system, and be easily integrated into an existing platform, serving a vast number of clients and presenting very good performance.

1.3 Project Presentation

This dissertation work was performed in the context of a more comprehensive project, named Infrastructure for Client-Based Desktops (iCBD) [36]. The iCBD project is being developed in collaboration between the *NOVA LINCS Research Center*, hosted at *DI - FCT/NOVA*, and *SolidNetworks – Business Consulting, Lda.*, a subsidiary of *Reditus S.A.*.

The project’s primary objective is to develop a winning VDI product that separates itself from the current solutions (that we have dubbed server-based VDI), which execute the virtual desktops in large, resource-heavy, servers. iCBD’s approach, which we dubbed client-based VDI, supports the execution of both native (Linux only) and virtual desktops (any “virtualizable” OS) on the user’s physical computer, in a nonintrusive way.

1.3.1 iCBD Project

There are some leading-edge aspects of the Infrastructure for Client-Based Desktop project which sets it apart from other existing ones such as the adoption of a diskless paradigm with a remote boot, the way the platform stores Virtual Machine images, and the support for virtualised or native execution on the target workstation¹, depending on

¹In this document workstation is a user’s desktop PC, laptop, etc., any PC compatible computing device with a recent enough architecture that support modern hypervisors.

the user's choice. [35]

The remote boot of the user's workstation requires the cooperation of HTTP, TFTP, DHCP and the image repository servers - the ones that store both read-only VM templates and writable space for running instances started from those templates. Communication between workstations and the platform is over the HTTP protocol, providing both flexibility and efficiency. [3, 35, 37]

In short, the primary objectives of the project are:

- Offering a work environment and experience of use so close to the traditional one that there is no disruption for the users when they begin to use this platform.
- Enabling centralised management of the entire infrastructure, including servers, in their multiple roles, storage and network devices, all from a single point.
- Completely decouple users and workstations in order to promote mobility.
- Support disconnected operation of mobile workstations.

When all these objectives are taken into account, there is a clear distinction from other solutions currently (and previously) available. As far as we know, no other solution is so comprehensive in the use of the resources offered by the physical workstations whether they are PCs, laptops or similar devices.

1.3.2 Previous Work

The iCBD project started about two years ago, and there has been a lot of work in that period, namely by DI-FCT/NOVA students. Previous work was focused on the creation of the instances of virtual machines, using either the storage system's snapshot mechanisms (for those where native snapshots were available) or the hypervisor's own mechanism. These studies resulted in two MSc dissertations, one carrying out a more in-depth study of Btrfs (and other file systems) while the other focused itself in object-based storage, particularly on the Ceph (RADOS) product.

These two avenues, file system and object-storage system, proved themselves well suited for the iCBD project, and resulted in the next step, namely on how to support a multi-node, scalable, and failure-tolerant iCBD infrastructure, one where nodes may be geographically dispersed.

1.4 Problem Stating and Main Contributions

This dissertation aims to build upon the previous contributions, deeply study the core of the iCBD platform, and tackle the next set of questions, mainly:

- *In a geographically dispersed, multi-server iCBD infrastructure, how do we keep the VM templates consistent and available even on the presence of network faults?*
- *How do we keep a simple management interface in a distributed platform?*
- *How to scale the platform in order to handle a large number of clients and maintain or even enhance its performance?*

1.4.1 Replication and Caching - The Problem

To address the previous questions, we start with a known fact: providing high availability for data requires redundancy, and the simplest way to provide redundancy is to have replicas. Therefore, building a replication mechanism is clearly our starting point. With that in mind, we tackle a second part of the problem: if we want to provide to the iCBD clients (workstations) fast access to the data, that data must be moved, or cached, near those clients. Now, if our cache stores the full data objects that the client needs, and not just parts of those objects, caching becomes just a side-effect from replication.

Establishing Goals Providing a mechanism that ensures the correct replication of data between nodes of the platform is of paramount importance; but other objectives, such as achieving the best performance possible on data transfer operations – that is, transfer speed must be maximised, and the amount of data moved around should be minimised, and the process should not be computationally intensive – are also important. Another goal is ease of integration of the replication process with multiple technologies: the iCBD storage layer is open to different storage backends – we already mentioned Btrfs and Ceph. So, the design of the replication module should strive for an API that eases the integration with different backend technologies, as long as these do provide a snapshotting mechanism.

As far as caching is concerned, two problems must be addressed: how to plan the number and location of cache (i.e., replica) servers, and which platform services are fundamental for running images on the user's workstations and how can they be integrated with the replication and caching infrastructure in order to deliver the best possible experience to the highest number of clients.

To summarise, the following list expresses the key requirements that must drive the architecture, design, planning and execution of (the rest of) our work:

- The iCBD platform needs to be always available and maintain top-notch performance in multiple locations, while serving a considerable number of clients.

- There are two main reasons for data replication: fault-tolerance (replicas represent backups) and moving data closer to the clients.
- Taking for granted that data is close to the consumer, devise ways to deliver that data (to the client) as efficiently as possible.
- Booting a client should require the smallest number of platform functionalities possible, simplifying the boot process near the consumer.

1.4.2 Main Expected Contributions

The main expected contributions are:

- Perform a throughout analysis of the iCBD platform layers and modules that are already implemented, in order to understand its internals, to document it and allow an efficient planning of the remaining of our work.
- Study, develop, and evaluate an implementation of a distributed and replicated storage platform to support VMs, built on top of Btrfs.
- Implement a client-side caching solution in order to increase availability, improve response time, and enable better management of resources.
- Integrate the solutions described above with the previous work and the existing infrastructure.
- And, finally, carry out a series of tests that a) allow us to assert that our replication and caching system is functionally complete and stable enough for production use, b) allows us to draw meaningful conclusions about its performance, and c) provide us with hints for future enhancements of the iCBD platform.

1.5 Document Structure

The rest of the document is structured as follows:

- **Chapter 2 Research Context** - This chapter presents existing technologies and theoretical approaches which were studied; examples include storage systems and their features, and details on virtualisation techniques and hypervisors.
- **Chapter 3 iCBD - Infrastructure for Client-Based Desktop** - In this chapter, we present the iCBD platform: we start with an overview of the solution, describe the multiple layers and explains the conceptual and architectural decisions that were made. This chapter is essential to the understanding of the bigger picture and where our work fits in.

- ***Chapter 4 Implementation of the iCBD-Replication and Cache Server*** - We start with an in-depth view of the implementation of the iCBD Replication module, detailing the architectural decisions and the implemented components. Then, a description is given on the efforts to build, on the FCT NOVA campus, a server infrastructure exclusively dedicated to the iCBD project. Then we explain how to build and deploy the iCBD Cache Server software for a node that will support a student's computer lab with 15 workstations in the Computer Science Department.
- ***Chapter 5 Evaluation*** - In this chapter, we present the evaluation process employed to validate our Implementation, with an emphasis on the analysis of the results we obtained and a comparison with the baseline values.
- ***Chapter 6 Conclusions & Future Work*** - This chapter concludes the dissertation; we provide the answers to the questions we raised in the Introduction, summarise the results achieved in the evaluation process, and recall some ideas for further improvements, ones that were formulated during the implementation process, and we believe are a good starting point for future work.

RESEARCH CONTEXT

The focal point of this dissertation is the implementation of a scalable and coherent distributed data store on top of a set of local (and independent) file systems. The file systems, however, are not used for "general purpose" work: in our deployment, they store VMs - (1) their read-only base images (or templates) and / or (2) their running instances backstores and / or (3) their "support files" (VM specifications, Non-Volatile Random-Access Memory (NVRAM) / Basic Input/Output System (BIOS) images, etc). Furthermore, the target file systems are those which are able to natively provide snapshots and, for the purpose of this dissertation our choice was Btrfs.

Moreover, our work should integrate smoothly into a broader infrastructure illustrated in detail in Section 3. In this chapter, we start with a survey of core concepts directly associated with the thesis and compliment with some analysis on the state-of-art in the relevant fields. The organisation of this chapter is as follows:

Section 2.1 overviews virtualisation as a core concept, describing significant properties and the inner works of hypervisors and finishes with a comprehensive discussion about the multiple VDI models.

Section 2.2 studies the principal challenges for a storage system in a VDI context and makes a survey of the multiple types of file systems which are currently prevalent in a data centre environment.

Section 2.3 talks about the problem of the locality of the data, and how that fact can influence the performance and scalability of a system.

Section 2.4 expands on the fact the storing data in a single location is not enough for compliance with current requirements, such as high availability, fault tolerance and performance standards in critical systems.

2.1 Virtualisation

Most of today's machines have such a level of performance that allows the simultaneous execution of multiple applications and the sharing of these resources by several users. In this sense, it is natural to have a line of thought in which all available resources are taken advantage of efficiently.

Virtualisation is a technique that allows for the abstraction of the hardware layer and provides the ability to run multiple workloads on a shared set of resources. Nowadays, virtualisation is an integral part of many *IT* sectors with applications ranging from hardware-level virtualisation, operating system-level virtualisation, and high-level language virtual machines.

A Virtual Machine, by design, is an efficient, isolated duplicate of a real machine [44], and therefore should be able to virtualise all hardware resources, including processors, memory, storage, and network connectivity.

For the effort of managing the VMs, there is a need for a software layer that has specific characteristics. One of them is the capability to provide an environment in which VMs conduct operations, acting both as a controller and a translator between the VM and the hardware for all *IO* operations. This piece of software is known as a Virtual Machine Monitor (VMM).

In today's architectures, a modern term was been coined, the *Hypervisor*. It is common to mix both concepts (*VMMs* and *Hypervisors*), as being the same, but in fact, there are some details that make them not synonymous. [2]

2.1.1 Hypervisors

The most important aspect of running a VM is that it must provide the illusion of being a real machine, allowing to boot and install any Operating System (OS) available for the real hardware. It is the VMM which has that task and should do it efficiently at the same time providing this three properties [44]:

Fidelity: a program should behave on a VM the same way or in much the same way as if it were running on a physical machine.

Performance: the vast majority of the instructions in the virtual machine should be executed directly by the real processor without any intervention by the hypervisor.

Isolation: the VMM must have complete control over the resources.

A hypervisor is, therefore, both an Operating System and a Virtual Machine Monitor. It can be deployed on top of a standard OS, such as *Linux* or *Microsoft Windows*, or in a bare metal server.

To start a VM, the hypervisor kernel spins up a VMM, which holds the responsibility of virtualising the architecture and provide the platform where the VM will lie. Thus,

since the VM executes on top of the VMM, there is a layer of separation between the VM and the hypervisor kernel, with the necessary calls and data communications taking place through the VMM. This feature confers the necessary degree of isolation to the system. With the hypervisor kernel taking care of host-centric tasks such as *CPU* and memory scheduling, and network and storage data movement, the VMM assumes responsibility to provide those resources to the VM.

An hypervisor can be classified into two different types [8], depicting two virtualisation design strategies, as shown in Figure 2.1:

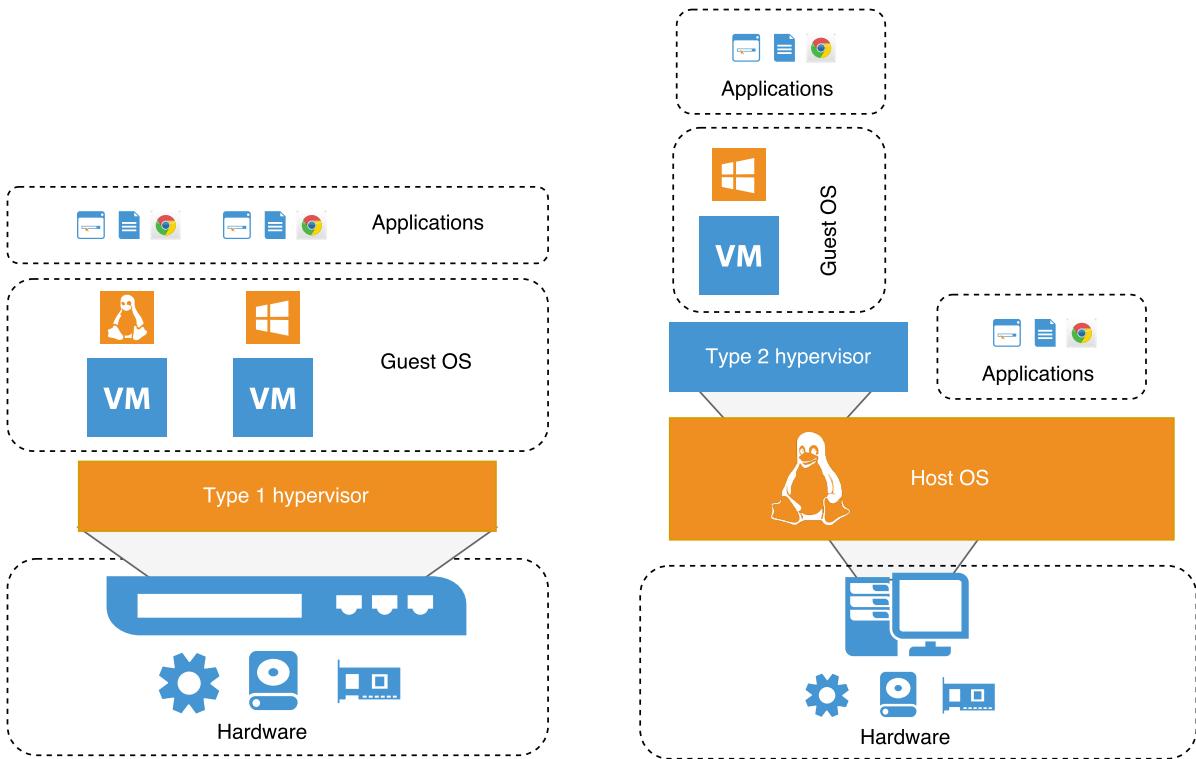


Figure 2.1: Virtualization architecture with type 1 and type 2 hypervisors

Type 1 hypervisor: Sometimes referred as a bare-metal hypervisor, since there is no need to rely on a host operating system, as it runs directly on the hardware. Moreover, it is the only program executed by the CPU in its most privileged mode. As there isn't any layer between the hypervisor and the resources, this type of hypervisor presents a more efficient solution than the Type 2.

In addition to the improved performance provided by the sharing or partitioning of devices between the several guest VMs, this architecture provides the benefit of supporting the execution of real-time OSs. The low-level nature of these hypervisors with the broad access to the hardware has proven useful for use-cases that need to deploy a multiplicity of operating systems even in mission-critical circumstances.

Recognising all the facts above, we can point that there are also some disadvantages. Any drivers needed to support different hardware platforms must be covered by the hypervisor package.

Type 2 hypervisor: This second variant of the hypervisor model relies on an already installed operating system and acts very similarly to any conventional process. Here, the hypervisor layer is a union of a host operating system with specialised virtualisation software, including extensions to that OS kernel, that will manage the guest VM. In this case, the hypervisor makes use of the services provided by the OS, which leads to a more significant memory footprint when compared to Type 1 but is integrated seamlessly with the remainder of the system. An excellent illustration of this kind of paradigm is Oracle VirtualBox and VMware Workstation/Fusion [2].

In this architecture, the host operating system retains ownership of the physical components, with each VM having access to a confined subset of those devices, and the virtual machine monitor providing an environment that emulates the actual hardware per VM.

All the above culminates in some advantages: Type 2 hypervisors are regularly deployed on desktop and laptop class of hosts, allowing: simulation of a rather complex testing virtualised systems without the expense and complexity of managing dedicated hardware; seamless integration with a graphical environment; host-guest file and print sharing.

Either way, the challenge lays in the fact that the hypervisor needs to provide to guest OS a safe execution environment and at the same time create different machine configurations to each one of them. These characteristics, such as the number and architecture of virtual CPUs (vCPU), the amount and type of memory available (vRAM), the allowed space to store files (vDisk), and so on, are user configurable but it is the job of the hypervisor to do all the resource management. The settings of these individual components reside in a VM configuration file. In the case of VMware hypervisors, the file has the .vmx extension,[45, 60] while in a KVM environment, that configuration is stored in a .xml file. [13]

With a virtualised infrastructure there is an opportunity for a substantial reduction in the number of servers which, in turn, diminishes the setup time as those VMs are, in a broad manner, created simply by cloning techniques. Software updates can be hugely simplified and made available to all VMs at once if those VMs are created on-demand from up-to-date templates at the beginning of a user session.

2.1.2 Virtual Desktop Infrastructure

It is common to find in a typical midsize corporate infrastructure hundreds of servers and thousands of workstations. All in a diverse ecosystem counting with many hardware

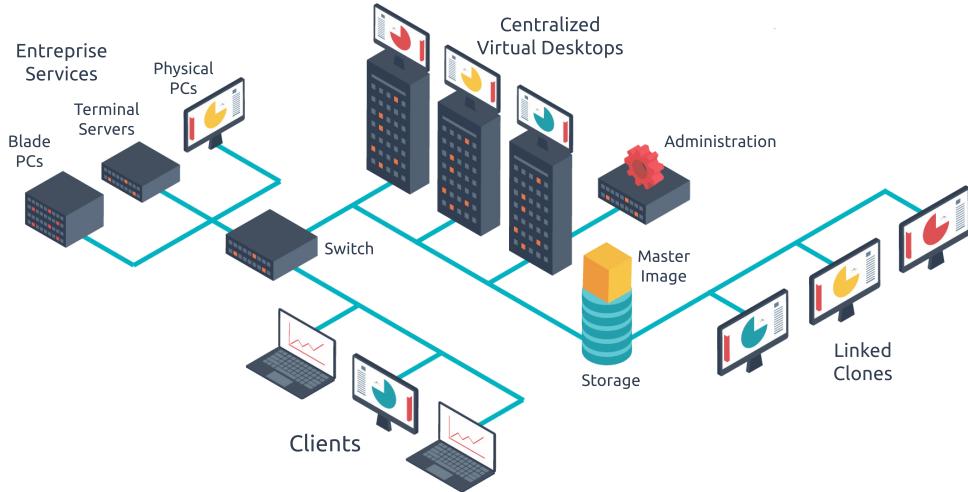


Figure 2.2: An example of a Virtual Desktop Infrastructure, adapted from AppDS [9]

configurations, different OSs and applications needs. Probably even supporting several versions of the same software is required for the day to day operations.

Organisations struggle daily with the traditional problem of installing software in local workstations disks one-by-one (even if employing an automated process). This task tends to be daunting as a company escalates in size and leads to some other predicaments:

- A Systems Administrator and IT Staff burden with significant infrastructure administration responsibilities and technical skills.
- A delay on the installation or reinstallation of new software and recovery from breakdowns or administration mistakes, which in large installations such intervention could take days.
- Installation processes may consume much of the available bandwidth in a network, so if this job is to be executed simultaneously on several workstations, it tends to be scheduled to off work hours to avoid disturbances.
- Periodical software updates (such Microsoft's famous Patch Tuesdays [42]) are ordinarily released in the morning's first boot of a workstation, which can bloat the traffic and render useless the workstation for the remainder of the update period.
- If an update proves to be undesirable, by introducing some unexpected behaviour, it is quite difficult to reverse this situation, which may even demand a new configuration infrastructure-wise.

One solution to the unpleasant situations outlined above is to minimise the footprint of installed software and reduce its managing needs. It is possible to conceive all the

software required to run a workstation (Operating System and applications) packaged in a single unit like a Virtual Machine. This mechanism allows for the virtualisation of a workstation that can be executed either locally on a typical PC / Laptop, or on a server. The most relevant approach and with more expression at the moment is the Virtual Desktop Infrastructure (VDI).

The concept encompasses a series of techniques, providing on-demand availability of desktops, in which, all computing is performed employing virtual machines [25]. Typically this solution offers a centralised architecture, where users desktops run in VMs, the user's environment resides on a server in a data centre, as shown in Figure 2.2. However, other components are required, such as storage for the users and VMs data and a network capable of moving large data blocks quickly, all in a perspective where from the user's viewpoint there can't be any apparent difference between a virtual desktop and a local installation.

There are two antagonistic approaches to the architecture, one focused on the server-side and the other on the client-side but both solutions are in an in-house paradigm were all configurations, management and storage needs are the responsibility of the business IT staff. A third approach emerged in recent years, with the peculiarity of being cloud-based, coined Desktop as a Service. In this section, we present a summary of the technologies above-mentioned.

Server-based VDI This is the most common approach, in which the VM runs remotely on a server through a hypervisor. In this model, the images for the virtualised desktops remain deposited in a storage system within a Data Centre. Then, when the times comes for the execution of such VM, a server that is running a hypervisor provisions the VM from storage and puts it into action. Featuring such benefit, as the fact that only a low-performance thin client with support for a protocol such as Remote Desktop Protocol (RDP) [46] or the Remote Framebuffer Protocol (RFB) [55] is required to interact with the virtual desktop.

The downside involves the costs necessary to maintain the service. Highly capable support infrastructure is needed (computing, storage, networking and power). With the additional requirement, of a need in some use cases, for adding high-end graphics processors to satisfy the workflow of customers using multimedia tools. We can still observe that the totality of the computing capacity of the hardware already present in the premises of a client prevails not harnessed. Of course, the machines already present can continue to be used, since they naturally have the resources to use the tools mentioned above, but the non-use of their full potential makes for all past investment made in hardware that pointless.

There are plenty of commercial solutions that use this principle, with the three most significant players being VMware's Horizon platform [58], XenDesktop from Citrix [62] and Microsoft with Microsoft Remote Desktop [41].

Client-based VDI In this model, the VM that contains the virtual desktop is executed directly on the client's workstation. This machine makes use of a hypervisor that will wholly handle the virtual desktop.

Since all computing work predominates on the client side, the support infrastructure (as far as servers are concerned) in this model has a much smaller footprint, having only as a general task to provide a storage environment. Alternatively, all the data could be already locally present in the hard drives of the clients, almost disowning the servers to sheer administration roles and the maintenance of other services.

The advantages remain close to the previous solution, with the added benefit of a reduced need for resources and the possibility of using some already present in the infrastructure. Although this approach presents itself as significantly more cost restrained, there isn't a notable adoption by software houses in developing products in this family. Reasons for this fact can be attributed to the implementation of such solutions that required a more complicated process, sometimes claiming the complete destruction of locally stored data on workstation hard disks. [14]. An example is a previously existing solution by Citrix, the XenClient [62].

Desktop as a Service The third, and most modern, concept incorporate the VDI architecture with the made fashionable cloud services. In some aspects shows some astonishing similarities to the server-based method, where servers drive the computation, but here, the infrastructure, the resources and the management efforts are located in the midst of a public cloud. An example of this design pattern is shown in Figure 2.3.

The points in favour are some: There is good potential for cost reduction in the field of purchase and maintenance of infrastructure since those charges are imposed on third parties. Every subject related to data security is also in the hands of the platform providers. Enables what is called zero clients, an ultrathin client, typically in a small box form factor, which the only purpose is to connect the required peripherals and rendering pixels onto the user's display. [63] With the added benefit of presenting very competitive costs per workstation when compared to other types of clients (thick and thin clients) and a reasonable saving on energetic resources.

However, in contrast, the downsides are also a few. Since the data location frequently is in a place elsewhere from its consumption, some bandwidth problems can arise, limiting the ability to handle a large number of connections. Adding to this mix is the issue of the unavoidable latency, a result of the finite propagation speed of data, which tends to escalate with the distance required to advance. Also, there is the jitter factor, caused by latency variations, which are observed when connections need to travel great lengths through multiple providers with different congestion rates. All these facts not only may lead to a cap on the numbers of clients

that are able of connecting simultaneously but also can be a motive in a diminished experience and quality of service provided, when in comparison to the previously presented solutions.

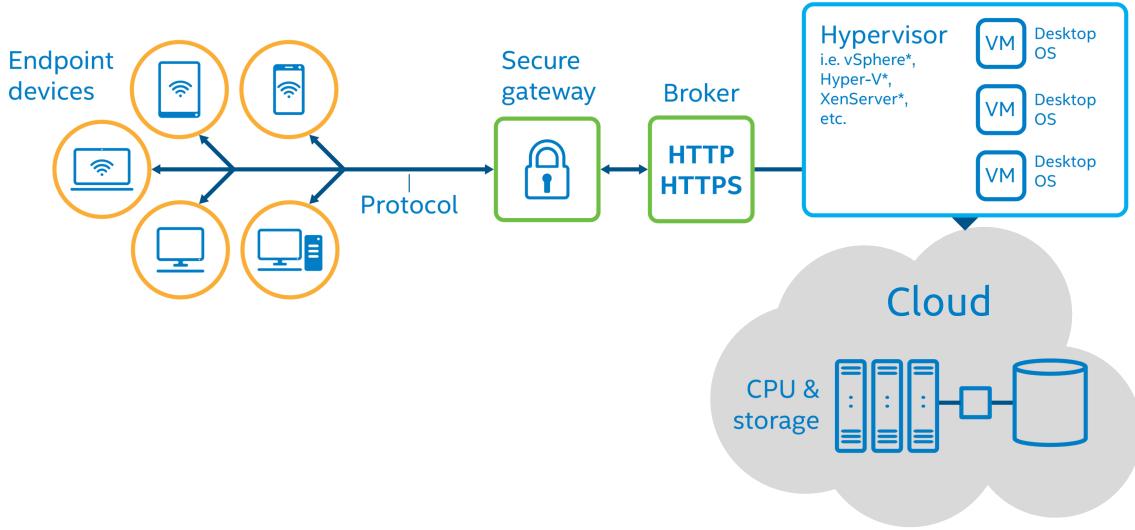


Figure 2.3: Conceptual overview of DaaS architecture, adapted from Intel [30]

In this new field, a multitude of solutions is emerging with public cloud providers leading the way. Amazon in its AWS portfolio delivers Amazon Workspaces [6], and Microsoft implements the RDS features [40] on the Azure product line. Nevertheless, there are also some smaller contenders, as an example, Workspot [61] (a company founded by ex-Citrix employees) makes use of the Microsoft Azure Cloud to provide there take on cloud-native Virtual Desktops.

2.1.3 Virtual Machine Image Storage

The data storage is one of the focal points to address in this work. Therefore, it is meaningful to understand how a virtual machine is composed and how is translated to a representation in a storage device.

The basic anatomy of a Virtual Machine encompasses a collection of files that define the VM settings, store the data (i.e. Virtual Disks) and save information about the state of its execution. All of these data and metadata need to be deposited on storage devices of whatever type.

VMware Architecture Given the architecture presented by VMware software [60], the main files required for the operation of a VM are:

- *The VM configuration file* - The .vmx file holds the primary configuration options, defining every aspect of the VM. Any virtual hardware assigned to a VM is present here. At the creation time of a new virtual machine, the configurations regarding the guest operating system, disk sizes, and networking are appended to the .vmx

file. Also, whenever an edit occurs to the settings of a virtual machine, this file is updated to reflect those modifications.

- *The virtual disk files* - Embodying multiple .vmdk, which stores the contents of the virtual machine's hard disk drive and a small text disk descriptor file. The descriptor file specifies the size and geometry of the virtual disk file. Also includes a pointer to the full data file as well as information regarding the virtual disks drive sectors, heads, cylinders and disk adapter type. The virtual disk actual data file is conceived while adding a virtual hard drive to a VM. The size of these files will fluctuate based on the maximum size of the disk, and the type of provisioning employed (i.e. thick or thin provisioning)
- *The file that stores the BIOS* - The .nvram file stores the state of the virtual machine's BIOS.
- *The suspended state file* - The .vmss saves contains the state of a suspended virtual machine. This file is utilised when virtual machines enter a suspended state giving the functionality of preserving the memory contents of a running VM so it can start up again where it left off. When a VM is returned from a suspend state, the contents of this file are rewritten into the physical memory of the host, being deleted in the event of the next VM Poweroff.
- *Log files* - A collection of .log files is created to log information about the virtual machine and often handled for troubleshooting purposes. A new log file is created either during a VM power off and back on process, or if the log file stretches to the maximum designated size limit.
- *The Swap file* - The vswp file warehouses the memory overflow in case the host cannot provide sufficient memory to the VM, and Ballooning technique cannot be employed to free memory [27]

In addition to the records described above, there may be some more files associated with the use of snapshots. More concretely, a .vmsd file and multiple .vmsn. The first is a file with the consolidation of storing and metadata information about snapshots. The other one, represents the snapshot itself, saving the state of the virtual machine in the moment of the creation of the snapshot.

The implementation of snapshots mentioned above applies to a specific implementation of VMware and takes form as follows: first, the state of the resource is stored in the form of an immutable and persistent object. Then, all modifications that transform the state of the resource are gathered in a different object. The diverse snapshotting techniques are addressed in a more comprehensive sense in the Section 2.2.3.

2.2 Storage

As stated in previous sections, the main problem to be addressed in this work is the storage concerning virtual machines. That could be either images, snapshots, files or data structures that are needed to support the execution of a VM.

When applied to the VDI concept some demands appear in the form of specific care needed at planning the storage system architecture, as well as the supporting infrastructure: the hardware picked, network topology, protocols used, and software implemented.

At the end of the day, the idea is to present a solution that offers an appropriate cost to performance ratio, and that with little effort can scale when the need emerges.

2.2.1 Storage Challenges

I/O Storms In a typical data centre application, with a well-designed infrastructure and in normal conditions, the storage system is steadily used but isn't being stressed continuously with I/O requests that directly affect the system performance. However, that postulate is no longer valid when talking about the storing of VM files for use in a VDI environment. In this type of context, some events can cascade in I/O storms that eventually introduce degradations in storage response time, which diminishes the performance of the overall system and in turn leads to a lower satisfaction level for the users of said system. From several events that influence a storage system we can point out some that have more expression in a VDI setting:

Boot Storm It may happen, on the occasion of the starting a work shift; with several users simultaneously arriving at their desk and booting their workstations. In this circumstance, all VMs are simultaneously performing multiple read and write operations on the storage system, which translates into poor response times and a long wait for the end of the boot process.

Login Storm Right after the booting an OS, the workstations are not entirely operational users have to log in to access a desktop, including applications and files. This procedure, results in a considerable number of concurrent I/O requests from multiple VMs in a short time, as the system attempts to load quite a few files related to the user's profile.

Malware and Anti-Virus Software Scanning Usually scans for unwanted files and untrusted applications, are scheduled to execute at a time when they cause the least possible impact taking into consideration the load of the machine. However, it is not uncommon to observe a behaviour where this kind of software starts a scan right after boot. Alternatively, the unfortunate case where different machines decide to start that examination at the same time, causing a negative impact on every machine.

Big Applications Needs Some applications can be very I/O intensive, like loading a project in an IDE with numerous libraries and dependencies that need to be reviewed at startup. Also, we can envision a scenario where multiple users simultaneously open the same very resource intensive application, for instance, in a classroom, the teacher asks the students to start a particular application, the I/O requests to the storage system will most likely be simultaneous.

Operating System Updates Similarly to Malware and Anti-Virus Software Scanning, the update process of an Operating System will most likely be tied to a schedule that is based on the current load of a machine. Yet, multiple systems may decide to perform an update in the same space of time thus leading to the bottleneck problem of concurrent access to the storage system.

2.2.2 File Systems

The traditional and perhaps most common way of storing files and, in turn, VMs is the use of file systems. This kind of system is used to manage the way information is stored and accessed on storage devices. A file system can be divided into three broad layers, from a top-down perspective we have:

- The **Application Layer** is responsible for mediating the interaction with user's applications, providing an API for file operations. This layer gives file and directory access matching external names adopted by the user to the internal identifiers of the files. Also, manages the metadata necessary to identify each file in the appropriate organisational format.
- Then the **Logic Layer** is engaged in creating a hardware abstraction through the creation of logical volumes resulting from the use of partitions, RAID volumes, LUNs, among others.
- The last one is the **Physical Layer**. This layer is in charge with the physical operations of the storage device, typically a disk. Handling the placement of blocks in specific locations, buffering and memory management.

There are many different types of file systems, each one boasting unique features, which can range from security aspects, a regard for scalability or even the structure followed to manage storage space.

Local file systems: A local filesystem can establish and destroy directories, files can be written and read, both can move from place to place in the hierarchy but everything contained within a single computing node. Good performance can be improved in certain ways, incorporating caching techniques, read ahead, and carefully placing the blocks of the same file close to each other, although scalability will always be

reduced. There are too many file systems of this genre to be here listed. Nevertheless, some of the most renowned may be mentioned. As the industry-standard File Allocation Table (FAT), the New Technology File System (NTFS) from Microsoft, the Apple's Hierarchical File System Plus (HFS+) also called Mac OS Extended and the B-tree file system (Btrfs) initially designed by Oracle.

Distributed file system: A distributed file system enables access to remote files using the same interfaces and semantics as local files, allowing users to access files from any computer on a network. Distributed file systems are being massively employed in today's model of computing. They offer state-of-the-art implementations that are highly scalable, provide great performance across all kinds of network topologies and recover from failures. Because these file systems carry a level of complexity considerably higher than a local file system, there is a need to define various requirements such as being transparent in many forms (access, location, mobility, performance, scaling). As well as, handle file replication, offer consistency and provide some sort of access-control mechanisms. All of these requirements are declared and discussed in more detail in the book "Distributed Systems: Concepts and Design" by George Coulouris et al. [15]. We can give as example of file systems the well-known Network File System (NFS) [52] originally developed by Sun Microsystems, and the notable Andrew File System (AFS) [53] developed at Carnegie Mellon University.

There are numerous types of additional file systems not mentioned since they are not in the domain of this work. Still, it is important to note the existence of an architecture that is not similar to the traditional file hierarchy adopted in file systems, which is the object-based storage.

This structure, as opposed to the ones presented above, manages data into evenly sized blocks within sectors of the physical disk. It is possible to verify that it has gained traction leading to the advent of the concept of cloud storage. There are numerous implementations of this architecture, whether in small local deployments or large-scale data centres supporting hundreds of petabytes of data. This type of file system is being studied in the context of a parallel thesis but inserted in the same project already presented.

It is worthwhile to enumerate some examples such as CephFS [59], OpenStack Swift [54], and in a IaaS flavour the Amazon S3 [4] and Google Cloud Storage [18].

2.2.3 Snapshots

In this work, the snapshot functionality of the file system itself is a valuable asset. This technique is present in some of the most recently designed file systems, such as the Btrfs. As the name implies, a snapshot is an image at a given instant of the state of a resource, we are particularly interested in snapshots of volumes (logical disks), and of files (individually or grouped, for example, in a directory).

The implementation of a snapshot can be described as follows: a) the state of a resource is saved in the form of a persistent and immutable "object"; b) changes to the state of the resource forces the creation and storage of another object. Consequently, it is possible to return to any previous state, as long as, the object corresponding to that state is available. Snapshots are especially interesting in virtualised environments because the hypervisor can take snapshots of the most critical features of a VM: CPU, memory, and disk(s).

In this work, we propose to use the snapshot functionality of the file system itself, present in some of the most recently designed file systems, such as the Btrfs. This way the creation of linked-clones is handled by the file system capabilities as an alternative to linked-clones created by virtualisation software itself.

In order for multiple snapshots, do not take up space unnecessarily, data compression techniques are applied when implementing snapshots. So, the new object created to register the sequence of new changes of a resource only registers the modifications made, keeping unchanged the state in the initial (parent) object. This phenomenon (i.e. the changes between the current snapshot and the previous one) is called a "delta" connecting snapshots.

2.3 Caching

A cache can be defined as a store of recently used data objects that is nearby one client or a particular set of clients than the objects themselves. The inner works of one of these systems are rather simple. When a new object is obtained from a server, it is added to the local cache, replacing some existing objects if needed. That way when an object is requested by a client, the caching service first checks the cache and supplies the object from there if an up-to-date copy is available. If not, an up-to-date copy is fetched, then served to the client and stored in the cache.

Caching often plays a crucial role in the performance and scalability of a file system and is used extensively in practice.

Caches may be found beside each client or they may be located on a server that can be shared by numerous clients.

Server-side Cache: Server side caching is when the caching data occur on the server.

There is no right way to the approach of caching data; it can be cached anywhere and at any point on the server assuming it makes sense. It is common to cache frequently used data from a DataBase to prevent connecting to the DB every time some data is requested. In a web context, it is common to cache entire pages or page fragments so that there is no need to generate a web page every single time a visitor arrives.

Client-side Cache: Maintaining the analogy to the Web environment, caches are also used on the client side. For instances, Web browsers keep a cache of lately visited

web pages and other web resources in the client's local file system. Then when the time comes to serve a page that is stored in the cache, a special HTTP request is used to check, with the corresponding server, if the cached page is up-to-date. In a positive response the page is simply displayed from the cache, if not, the client just needs to make a normal request.

2.4 Replication

At the storage level, replication is focused on a block of binary data. Replication may be done either on block devices or at the file-system level. In both cases, replication is dealing with unstructured binary data. The variety of technologies for storage-level replication is very extensive, from commodity RAID arrays to network file system. File-based replication works at a logical level of the storage system rather than replicating at the storage block level. There are multiple different methods of performing this. And, unlike with storage-level replication, these solutions almost exclusively rely on software.

Replication is a key technology for providing high availability and fault tolerance in distributed systems. Nowadays, high availability is of increasing interest with the current tendency towards mobile computing and consequently the appearance of disconnected operation. Fault tolerance is an enduring concern for those who provide services in critical and other important systems.

There are several arguments for which replication techniques are widely adopted; these three are of significant importance:

Performance improvement: Performance improvement: Replication of immutable data is a trivial subject, is nothing more than a copy of data from one place to another. This increases performance, sharing the workload with more machines with little cost within the infrastructure.

Increased availability: Replication presents itself as a technique for automatically keeping the availability of data despite server failures. If data is replicated in additional servers, then clients may be able to access that data from the servers that didn't experience a failure. Another factors that must be taken into account are network partitions and disconnected operation.

Fault tolerance: There is the need to maintain the correctness guarantees of the data in the appearance of failures, which may occur at any time.

iCBD - INFRASTRUCTURE FOR CLIENT-BASED DESKTOP

The acronym Infrastructure for Client-Based Desktop (iCBD) stands for Infrastructure for Client-Based (Virtual) Desktop (Computing), a platform being developed by an R&D partnership between *NOVA LINCS*, the Computer Science research unit hosted at the *Departamento de Informática of Faculdade de Ciências e Tecnologia of Universidade NOVA de Lisboa (DI-FCT NOVA)* and *SolidNetworks – Business Consulting, Lda*, a subsidiary of *Reditus S.A.* group.

iCBD's primary goal is to implement a client-based VDI, a specialized form of VDI where all computing chores – from graphical display to application execution – are performed directly on the user's workstation (PC/laptop, etc.) hardware as opposed to performed on big and expensive servers, as it goes with mainstream VDI implementations such as the ones from Citrix, Microsoft or VMware, to name the most relevant ones. Furthermore, iCBD, while using the workstation's hardware, does not touch the disk – either to load software or as a temporary scratch device: it runs diskless. And, however, it does offer a simple and centralised administration of the infrastructure, even when it spans multiple sites.

This chapter will address the project's central concepts and associated technologies:

Section 3.1 overviews the project's core concepts and address note peculiarities and limitations of mainstream implementations in contrast with our approach.

Section 3.2 studies the main architectural components of the platform, with emphasis on the different layers and how they act together to serve the end-user.

3.1 The Concept

iCBD, as a project, aims to research an architecture that leads to the development of a platform that we call client-based VDI, while maintaining all the benefits of both client-based and server-based VDI. Additionally, it should be deployable as a Cloud Desktop as a Service (DaaS) without any of the drawbacks of current DaaS offerings.

In short, our aim is to preserve the convenience and simplicity of a fully centralised management platform for Linux and Windows desktops, instantiating those in the users' physical workstation from virtual machine templates (VMs) kept in repositories. We will further address this subject in Section 3.2.

To summarise the iCBD platform should be able to:

- Within the boundaries of the proposed architecture, adapt to a wide range of server configurations.
- Provide an user experience so close to the traditional one, that users should not be able to tell it from a PC standard (local) install.
- Simplify installation, maintenance and platform management tasks for the entire infrastructure, including servers in their multiple roles, storage and network devices, all from a single point of administration.
- Allow for a highly competitive per-user/workstation cost.
- Maintain an inter-site solution to support efficiently, e.g., a geographically disperse multi-site organisation.

3.2 The Architecture

The iCBD platform encompasses the use of multiple services; to achieve a better understanding of its inner workings, we can group these services in four major architectural blocks, as seen in Figure 3.1.

iCBD Machine Image (iMI) embodies the required files to run a iCBD platform client; this nomenclature was borrowed and adapted from Amazon Web Services' AMI [5]. An iMI includes a VM template (with an operating system, configurations and applications), the iCBD boot package (a collection of files needed for the network boot and tailored to the operating system) and an assortment of configurations for services like PXE and iSCSI.

Boot Services Layer responsible for providing the initial code that supports network boot of client machines, the transfer a bespoke follow-up package (OS, ramdrive, initial scripts), using services such as PXE, DHCP, TFTP and HTTP.

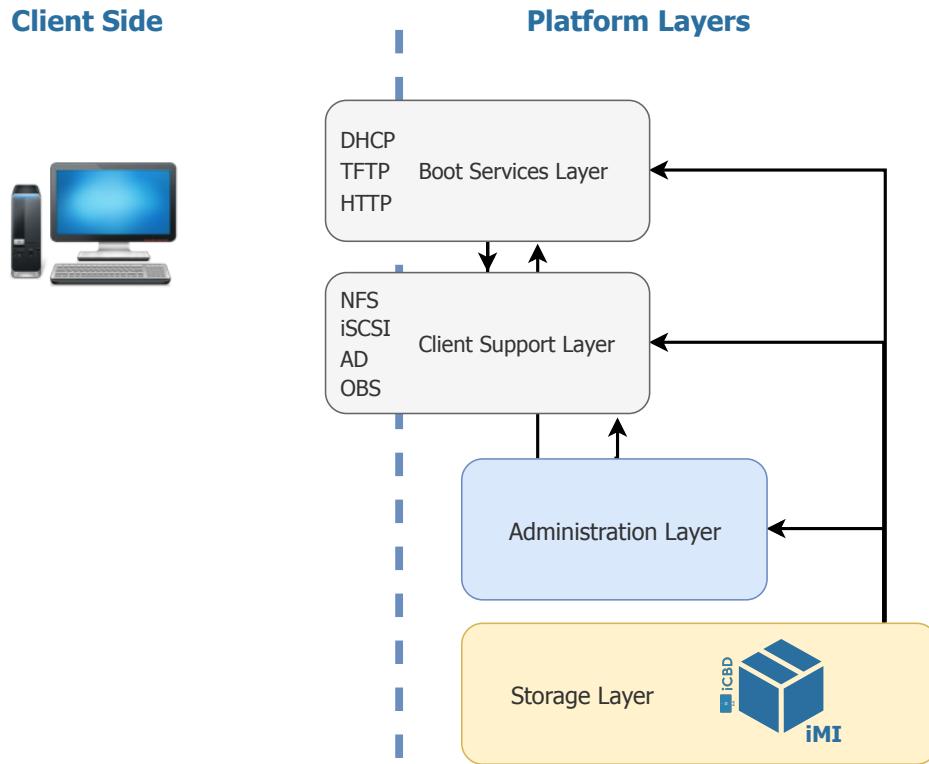


Figure 3.1: iCBD Layers View

Client Support Layer provides support for client-side operations including, e.g., authentication, read/write storage space for client instances (since iMIs run on "disk-less" workstations) and access to the users' home directories.

Administration Layer maintains platform users and the full iMI life cycle, from creation to retirement. Currently, administration is based on a custom set of scripts.

Storage Layer maintains the repository of iMIs and provides essential operations such as version control of the VM image files. Our work is fundamentally focused on this layer, extending it in such a way that a single repository abstraction can be built on top of the local/individual repositories through replication and caching. These local repositories are implemented on Btrfs or Ceph and may be exported to clients using NFS, iSCSI, REST and other suitable protocols.

In the next subsections, we will provide a more detailed description of each of the above-mentioned layers. x

3.2.1 iCBD Machine Image

In its essence, an iCBD Machine Image is an aggregation of everything that is needed to run an Operating System within the iCBD platform – kernel, binaries, data and configuration files. For the sake of simplicity, we categorise iMI files into three main groups:

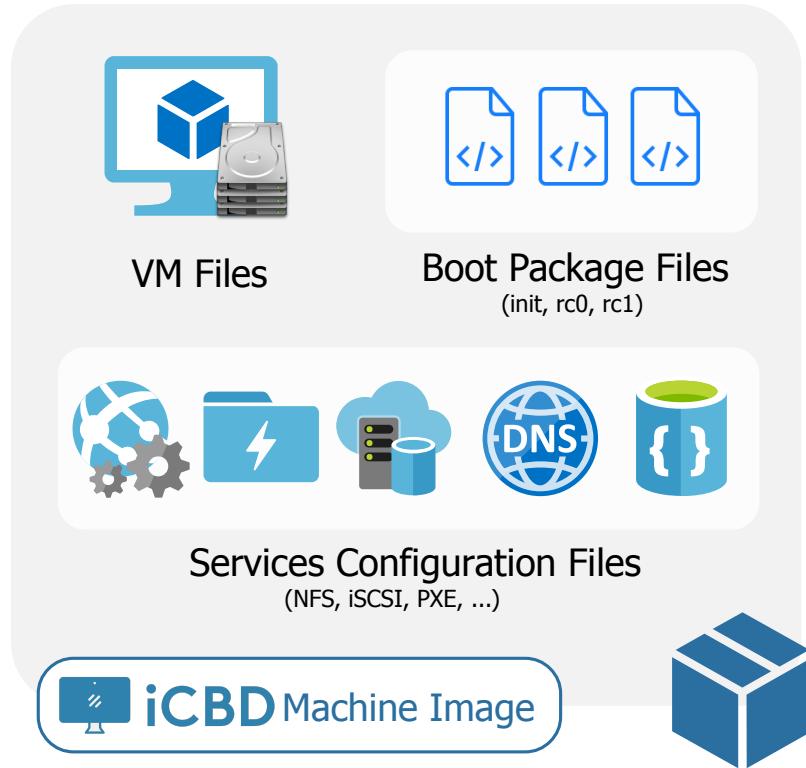


Figure 3.2: iCBD Machine Image Files

VM Template files The main component of this group is the virtual machine template in the form of a read-only image. As described in Section 2.1.3, the anatomy of a template follows the standard VMware and KVM formats either with multiple files (i.e., Virtual Disk Files like .vmdk or .qcow) or a *raw* storage format (a disk image).

iCBD Boot Package files In a network boot environment, such as the one used, there is a need to keep a set of files that manage the boot process of the user's workstation; these files can be included in the initial *ramdisk* or transferred over HTTP later on, when needed. Included in the boot package are: a *BusyBox* tool, an init file, and at least two Run Control Script files (*rc0* and *rc1*) that are responsible for starting network services, mount all file systems, and ultimately bring the system up into the single-user level. With *BusyBox* (a single executable file with a stripped-down set of tools), a basic *shell* is available during the boot process to fulfil all the required steps.

Service Configuration files The iCBD platform uses several services, and some do require particular settings in the configuration files. As an example, the "NFS exports" configuration file should reflect which file systems are exported, which networks a remote host can use, as well as a myriad of options that NFS allows; the same happens to iSCSI, where an iSCSI target needs to refer to a backing store for the storage resource where the image resides.

iMI Life Cycle The life cycle of an iMI encompasses all stages that take it throughout its course within the platform; Figure 3.3 shows the major ones, from creation, through deployment, when in use by multiple clients and, finally, its retirement and placement in to temporary or cold storage.

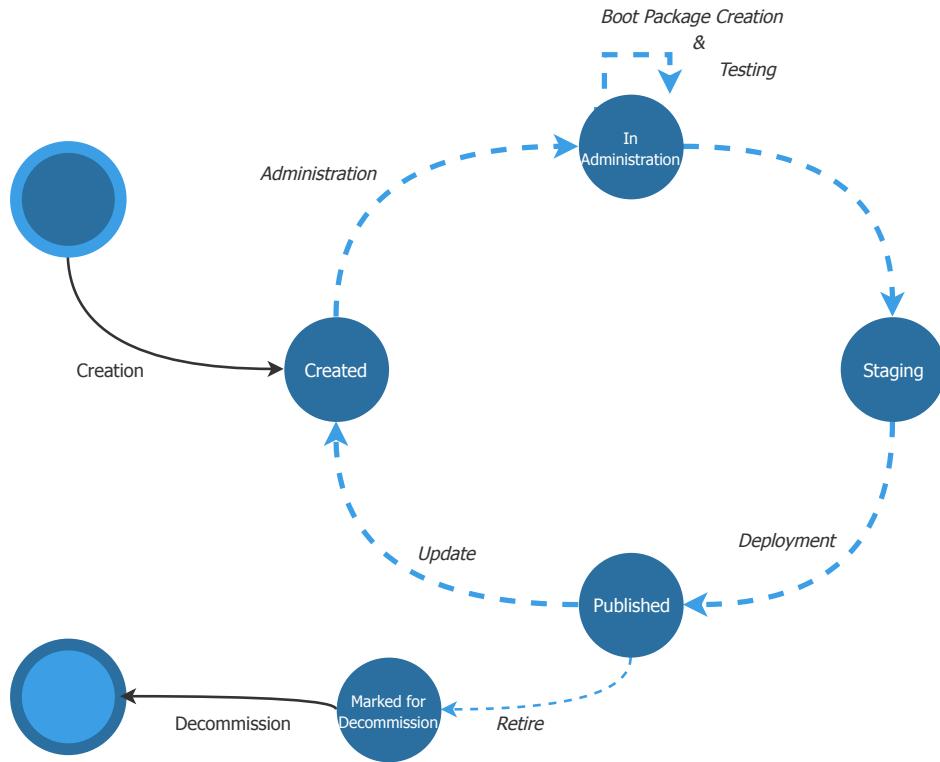


Figure 3.3: iMI Life Cycle inside the iCBD Platform

When an iMI completes a full cycle, a new version is created; so, every new update made to an iMI will spawn a new version. The creation of a new version is a rather straightforward and computationally light operation, thanks to the snapshotting features available at the storage layer.

During its life in the platform, an iMI can be in one of the following four main states:

Created After being inserted into the platform, an image is not instantaneously ready to be served to clients and booted in a workstation; it must pass through a number of administration steps for the generation of the appropriate boot package.

In Administration An iMI goes through this phase in two moments: the first one, described above, when an image has just been injected (created) into the platform; and the second, and most frequent case, when an image needs to be updated or, in any way, modified. The iMI will stay in this state as long as it is being managed, which can take from a few minutes to hours; at the end this process the boot package is automatically created.

Not Published This is the status of an image that is ready but isn't yet published, and is therefore not visible to platform users. This phase is of particular interest for testing it for correctness of the boot process, and to ensure that the modifications were, in fact, applied. Only after testing should an iMI made available for general use.

Published This state corresponds to the deployment of an iMI into production and is the one where the iMI is expected to spend most of its time. iMIs in this stage have their entries displayed at the user's workstation screen at boot time, and all the necessary support for their execution is available at the Boot Services Layer. So, if the user chooses one of those iMIs, no matter what device (e.g., PC or laptop) he/she is using, the image is expected to boot to completion, and the user should be able to login and work just as if the boot was from a local disk.

When an iMI completes a cycle and undergoes an update process, the old version is retired and set to a new state, named **Marked for Decommission**, which is comparable to a stay in limbo. First, because when the administration process was initiated clients could be using that same image, so it must be available for them (or else a disruption would happen). And, when the administration process finishes, clients may still be using the old version. Therefore, **Decommission** is only triggered when the last client "closes" its session. At that moment, the old version can be removed entirely from the platform or, more wisely, stored as a backup e.g., to allow the administrator to retrieve an older state of the image (for example, a newly installed update breaks some application).

3.2.2 Boot Services Layer

From an end-user perspective, the only layer that is visible and requires interaction, is the boot layer – one that displays the set of images the user is allowed to boot, and waits for his/her choice. However not every single aspect is noticeable: while this happens in the workstation's screen, in the background multiple services cooperate to run the chosen iCBD Machine Image.

The iCBD platform provides two distinct ways to remote boot an iMI: one instantiates, from an iMI, a native Operating System that runs on the workstation's "bare metal" just like a standard diskless network boot of, say, Linux does; the other uses the above mechanism to start a minimal OS with an embedded hypervisor installed, then runs the hypervisor, and finally launches another iMI, one chosen from those available in the platform. Both approaches are entirely transparent to the user and, users who are not knowledgeable about virtualisation technologies will be completely unaware of whether they are running a native or virtualised OS.

The first part of the boot process runs like any other network boot: a series of DHCP requests are used to provide suitable network parameters - particularly the location (IP address) of the TFTP server and, then, a small network boot manager program, is

transferred, loaded and executed. Using the standard PXE boot environment, a friendly looking, tailored graphical menu, displays an assortment of choices that announces the different iMIs ready to boot.

Booting an iMI in a Workstation After the selection, in the PXE [22] boot menu, of one of the available iMIs , the second-stage boot kicks in, using *PXELINUX* as a bootloader. That provides us with the capability of transferring a compressed Linux Kernel (*vmlinuz*) and an initial ramdisk (*initramfs*) [23] using either TFTP or HTTP. In this step, a number of parameters needed for proper operation are set with their appropriate values based on the requirements of the chosen image. After loading everything into memory (RAM), the second-stage boot loader runs the kernel image which, after initialisation, starts the first user-space application – usually, the init program.

In the iCBD platform init starts a chain of execution of two custom files, *rc0* and *rc1*; these Run Control scripts configure every single aspect in the OS according to the hardware characteristics of physical machine that is booting. The first step is to reconfigure the network interface card and obtain IP connectivity. Then, a check is performed to see if there is a need of getting more files to complete the boot process and, if necessary, those files are transferred. The next script, deals with data volumes and mounting operations – R/W space, user home directories, etc.. If the image’s OS is just the platform to run another iMI in virtualisation mode, more configuration steps are performed, e.g., a check is made to determine if the base OS file system happens to be Btrfs: if true, seeding must be used in order to create a R/W instance from an R/O iMI. Alternatively, or if the iMI OS is not Btrfs, an overlay filesystem is used to create the R/W instance.

After these configuration steps, the `switch root` command is executed moving the (already mounted) filesystems `/proc`, `/dev`, `/sys`, `/tmp` and `/run` to a new root and turning it into the new root filesystem, performing some housekeeping, namely erasing all files not in use in the *initramfs* root, releasing any unused memory.

Finally, the remaining configuration steps include setting of the current time with the NTP service and logging some statistics such as the elapsed time and the bandwidth consumed by the boot process as a whole.

3.2.3 Administration Layer

One of the most important features provided by the platform is the ability to perform administration operations on an iMI, a task accomplished with the help of an administration tool which enables an iCBD administrator (or architect, if we draw a parallel with a role commonly found in private cloud infrastructures) in an organisation to make the changes he/she deems necessary (e.g., update the OS and applications, add or remove software, and modify configurations) and then publish the new image (version) for widespread use.

The Administration Process The administration tool consists of a main script, `adm`, which then calls a series of others, depending on the task at hand. Calling `adm` with the name of one iMI as an argument starts an administration appliance - a VM with a custom-tailored base image that will support the administration process. Usually, the VM guest OS will be Linux, with several distributions supported: openSUSE Leap 42.2, Fedora 27, CentOS 7 and Ubuntu 16.04 LTS. The whole administration process makes extensive use of the snapshotting capabilities of the Storage Layer (whether using Btrfs or Ceph), with no (predictable) performance degradation on the other iCBD platform services.

For each iMI, there is a snapshot with an index number that relates to its version and age (i.e., higher numbers represent more recent versions); that index is used as the name of a directory, and the snapshot (and related files) are kept inside that directory. So, creating a new linked clone from the latest version of a VM becomes a very simple process.

When booted, the administration VM will start a hypervisor (VMware Workstation, VMware Player or KVM) and the hypervisor will be instructed to boot a linked clone created on-the-fly from the VM version (i.e., the iMI) that the administrator wishes to update. Thus, this process will, if executed in the iCBD administration server itself, use nested virtualisation [16] to achieve its goal, which may result in some performance degradation (even considering the use of a Type 1 hypervisor, such as KVM). However, in theory, nothing prevents the administrator from using his/her workstation in native mode or a server with a bare-metal hypervisor and run the administration VM using only one level of virtualisation.

In this step, the (newly created) snapshot being managed is in a temporary directory, one whose lifetime is the duration of the procedure. This method serves two purposes: first, all clients using the iMI version that is undergoing changes can keep using it; and, last, one may quickly discard all changes made in the working directory version if one wishes so.

When all modifications have been made to the temporary image, the administrator is given the option whether to commit or discarding them; if one commits, the temporary (working) directory is used to create a new linked clone (of the temporary snapshot), but one that follows the naming rules, and may, therefore, be used as the name of the new directory.

Creating the boot package After completion of the above-described steps, the iMI is not yet ready to be published, as there are no files to support the boot process; the next step is, therefore, the creation of a boot package. This is the responsibility of the `mki` script, one that, depending on the type of the iMI, may be called immediately when the Administration Process is over by the `adm` tool.

The procedure is different for Windows or Linux iMIs: while sharing a common set of steps, Linux iMIs require an additional number of customisation steps because iMIs for Linux have two sub-types – one for iMIs intended to run natively on a workstation, and

the other for IMIs that serve as hosts for other images. The first type requires the creation of custom `initramfs` and `vmlinuz` files, the addition of a subset of the image's Kernel drivers and firmware (namely for all available network interfaces and the filesystems used during the boot process), and the customisation of Run Control scripts (`rc0` and `rc1`) that start the network services with a suitable configuration, compatible with the iCBD platform, and mount the correct remote file systems. At the end of this process, a script called `runvmm` is also added; that script is instrumental in starting a virtualised iMI, as well as in configuring the hypervisor parameters in order to take advantage of the client's hardware.

However, the job of the `mki` script is not yet complete: for the two types of IMIs, the configuration of both the *iSCSI targets* (to reflect the new iMI version) and the *pxelinux* (to reflect the new paths to the files that will be served to the clients) must be updated.

3.2.4 Client Support Layer

The Client Support Layer is the most fluid of all layers, containing an aggregation of services (most of them originated outside the platform) working together to provide the environment that is required for a client workstation to operate correctly. Another essential service provided by this layer is its relation with storage layer, one which, using protocols such as NFS and iSCSI, allows the client to provide the necessary data for the boot process and obtain read/write space to support the changes made to the client's storage instance (derived from the iMI). Moreover, these protocols are the ones that provide access to the user home directory and other volumes, if supported.

It is important to note that there are other services that are essential to the correct operation of clients in the iCBD platform, such as DNS and NTP. And there are also services that, while not directly related to the iCBD platform, are nevertheless need to support clients; as an example, in a medium/large organisation Microsoft's Active Directory plays a paramount role – therefore it is necessary for the iCBD platform to coexist with this type of service, and Windows IMIs can be prepared in a way that, when an instance is booted, it will “automatically” join the organisation's AD.

3.2.5 Storage Layer

The most significant part of our work will focus on this layer, which is responsible for storing all platform data, whether they are IMIs, virtual disks (`.vmdk`) for VMs such as the administration VM and others that support platform services, databases that preserve information and configuration data for those services, code repositories, etc.. In its essence, the Storage layer consists of a set of file systems (or, if OBS-based, of object stores) each with its own purpose.

To keep this document short, we will only focus on file systems that provide storage for IMIs. Given the uniqueness of this type of data, the file system must have the right set of features, and of particular importance is the support for snapshots; as we have

previously referred, our choice is Btrfs. It is important to mention that this is not the only solution that supports snapshots – object stores such as RADOS (from Ceph) are particularly well suited to store very large objects, such as virtual disks, but that avenue is being researched in another project.

The Btrfs features that are heavily used in the iCBD platform are: sub-volumes; snapshots; cloning of both sub-volumes and snapshots; Btrfs seeding; and incremental backups, just to name a few. These features are used achieve several goals: multiple sub-volumes are used to store different parts of the platform data, snapshots are widely used to create (a kind of) version control for iMIs (allowing us to access any version at any moment) and to backup the entire iCBD platform. Btrfs seeding is another important feature, as it provides a mechanism that allows multiple read-only mounts of the same Btrfs file system, thus enabling multiple clients to use the same iMI.

One must remember that, while this work is focused on Btrfs, from the point of view of the remaining layers the type of store - filesystem or object-based - should be entirely transparent to the other layers, which will interface iCBD “data objects” through standard, widespread protocols such as NFS or iSCSI.

Therefore, when dealing with the problem of data replication across multiple file systems transparency, as an attribute, is fundamental. We will discuss in detail the replication and caching topics in the next chapter, and we will provide, then, an explanation of the decision-making process and a discussion on the implementation issues.

IMPLEMENTATION OF THE *iCBD-Replication and Cache Server*

This chapter is about the core of this thesis: the iCBD-Replication and Cache Server, a middleware system that provides replication features in an integrated way to the iCBD platform. Naturally, the first subsection provides a detailed description of the motivation, architecture and design aspects while the second subsection concentrates on the implementation. Finally, the last subsection deals with the process of building the Replication and Cache Server: that is, how the modules are installed and deployed in an iCBD infrastructure.

Section 4.1 begins by explaining the motivation for the implementation of a replication module within the iCBD platform, as well as explaining the need to include a new role in the platform with the creation and deployment of a cache server near the clients. Concluding with the overall architecture of the system and how both topics complement each other.

Section 4.2 overviews the implementation of the middleware dubbed iCBD-Replication. Beginning the journey through the initial architectural process and then showing the implemented components and their interaction with the several layers of the platform.

Section 4.3 shows how the complete iCBD platform was installed in the NOVA University cluster. Then, a description of the work performed to include a client-side caching server directly connected to the final clients.

4.1 Motivation and System Architecture

One of the key objectives of iCBD is to provide a platform that can stretch from a fully hosted, on-site architecture to one where an important part of its services is cloud-based. Naturally, in-the-middle solutions are also interesting, such as one where, e.g., both the administration and storage of “golden” iMIs are cloud-based, while the rest is on-premises. Therefore, it becomes evident that data locality is an important subject, and thus one must study how data flows between the components of the iCBD platform – a complex, data-intensive platform, boasting multiple storage devices and many different networks, accessed by multiple consumers demanding data at any given time.

All these factors, allied to the desire of having a distributed and scalable platform architecture, result in the need to design a new service whose mission is to ensure that data is correctly replicated in the appropriate places, and consistency of the various versions of the iCBD Machine Images stored is maintained. This led to the high-level architecture of Figure 4.1.

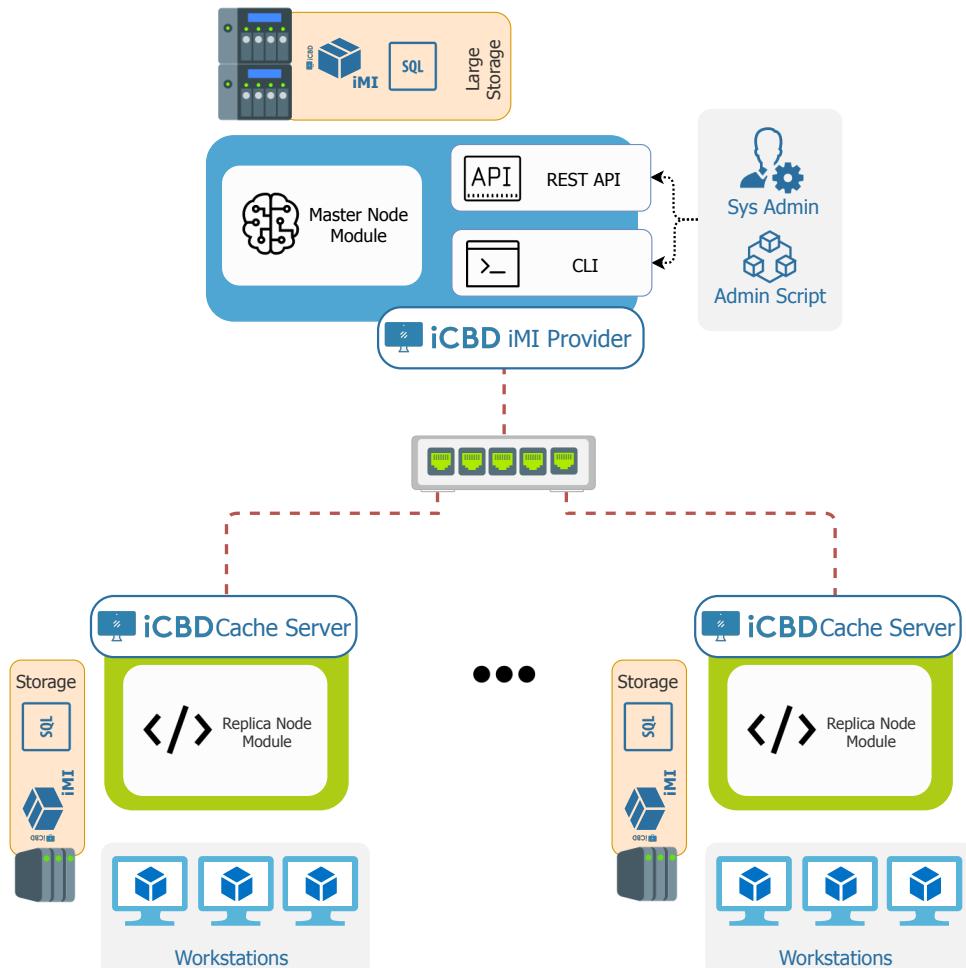


Figure 4.1: iCBD Replication and Caching Architecture (high-level)

4.2 Implementation of a Replication Module

When our project started, iCBD was already available; therefore, our Replication and Caching Service (from now on, RCS) had to be integrated with the existing architecture and support (and enhance) the previous work. This influences the choices available for the RCS implementation and could, in a worst-case scenario, severely limit them. Fortunately, that was not the case.

iCBD was designed from the start based on the assumption that the storage layer where iMIs live was built on top of a storage system which supports snapshots. In the first prototype, Btrfs was chosen for the storage layer but, in theory, any storage system that supports snapshots can be used in the platform. That is, in fact, the case with a parallel work being developed in another dissertation, where the focus is the use of an object-based storage system, Ceph.

4.2.1 Requirements

Btrfs is a modern file system based on the concept of copy-on-write (COW): it is capable of creating lightweight copies of filesystem structures – files, directories, volumes. We already detailed the importance of this trait in Section 3.2.5. Therefore, a mandatory step was to investigate Btrfs-provided tools that could help us to achieve our primary goal: being able to move information (“base” iMIs and their snapshots) around, from “master” to “secondary” nodes, while consuming the minimum bandwidth – one must not forget that, while a typical Linux iMI is less than 10 GB, a Windows 10 iMI is circa 40 GB. We found that Btrfs has incremental backup capabilities, and therefore we set out to explore those.

So, Btrfs’s incremental backup capabilities are a good starting point; however, their purpose is to help in data transfer; but that is not enough. Preservation of consistency of the iMIs is also a concern, as one has to assure that iMIs cached in the RCSs are up-to-date, and when a new iMI is created its distribution will start “immediately”, to ensure high availability in case of faults. Moreover, the locality of the data should be taken into account, since data transfer endpoints may be located within the same data centre, or at, e.g., geographically disperse regions in the world. Bandwidth use and data encryption become essential, requiring the study of compression algorithms and encryption techniques.

Btrfs Incremental Backup feature A first step is trying to understand the most efficient way to transfer this unique kind of data (i.e. an iMI). Given the fact that we are working with a file system with snapshots capabilities, we want to take advantage of this functionality and minimise the amount of data roaming the network.

Btrfs has a set of userspace utilities to manage Btrfs filesystems, called `btrfs-progs`; these include a pair of commands, `btrfs send` [34], and `btrfs receive` [33], that provide the capability to transport data via a stream and apply differences from/to a remote

filesystem. The send command simplifies the process of generating a stream of instructions that describe changes between two subvolume snapshots. Also available is the ability to use an incremental mode, where given a parent snapshot that is available in both the send and receive sides, only the small delta between snapshots (e.g. V2 and V2-1 in Figure 4.2) is going to integrate the stream. This feature considerably reduces the amount of information that needs to be transferred to reconstruct a snapshot in the receiving end. The send-side operations occur in-kernel, beginning by determining differences within subvolumes and, based on those differences, the kernel generates a set of instructions in a custom-formulated stream.

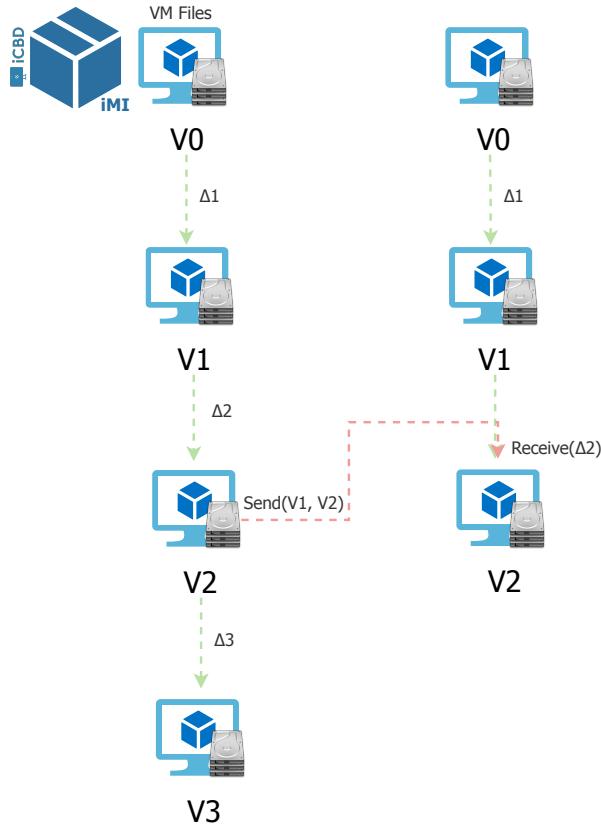


Figure 4.2: iCBD iMI Snapshots Structure

On the remote end, the receiving command accepts the stream generated by the send and uses that data to recreate one or more snapshots. Contrary to the send command, receive executes in user space, replaying the instructions in the stream one by one; the set of instructions includes the most relevant calls found in a Virtual File System, such as `create()`, `mkdir()`, `link()`, `symlink()`, `rename()`, `unlink()`, and `write()`, along with others [32].

4.2.2 System Overview

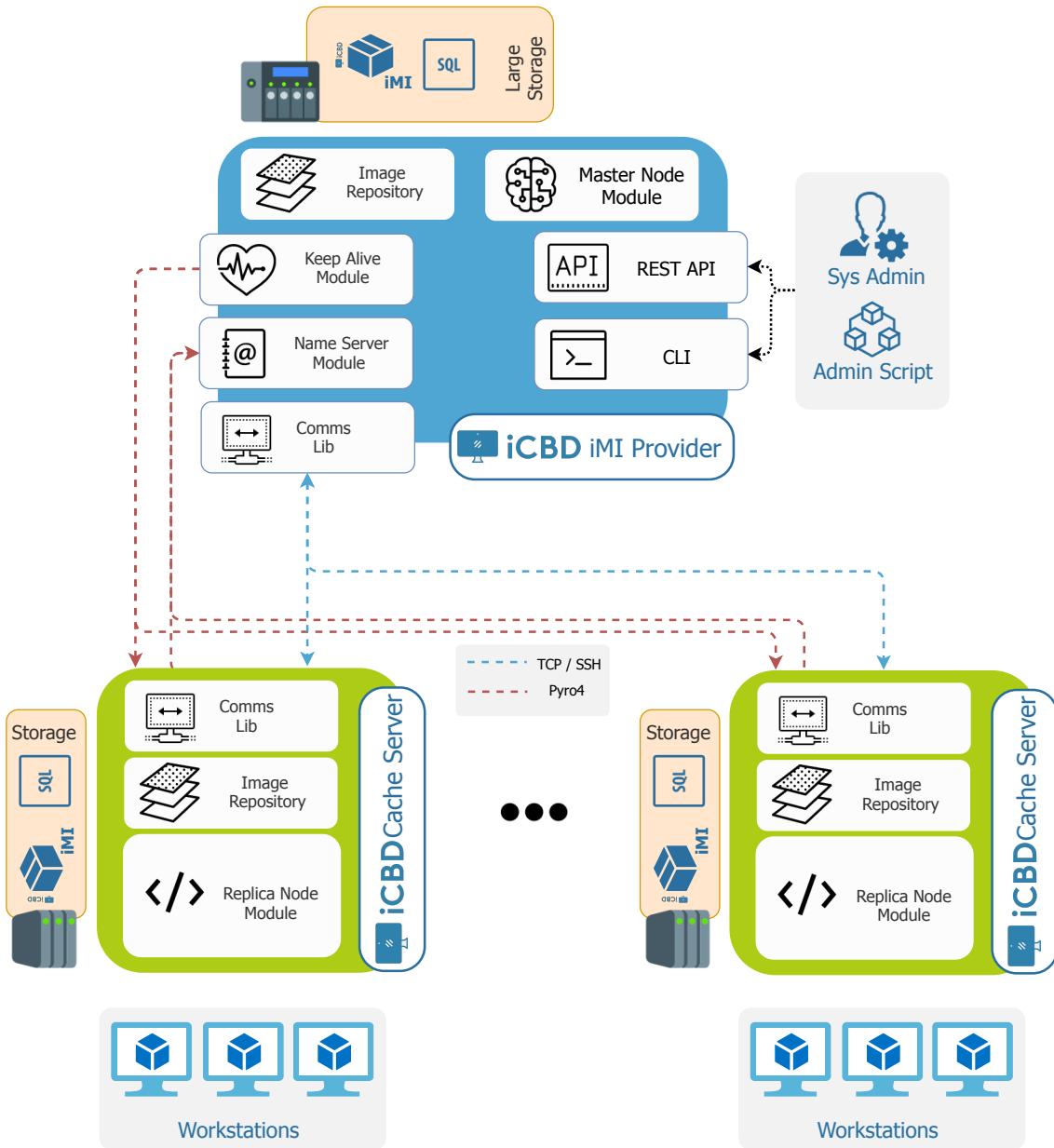


Figure 4.3: iCBD Replication Modules and Communications

Since the replication module interacts with different tools and utilities, e.g., bash scripts and command line tools and some OS calls, we think that the most suitable approach was to create a Python distributed middleware layer using a master-replica paradigm.

Python, as a programming language, enjoys some idiosyncrasies, functioning as an object-oriented language, possessing an extensive standard library and enjoying a big community delivering packages with a wide range of functionality; all these facts contribute to make it the most appropriate programming language to bind everything together in

our iCBD platform.

Our middleware is composed of several modules and includes all the necessary functionalities that allow a node to behave as a Master or as a Replica, where each maintains its individual Image Repository. A number of libraries were also developed: to interface with some tools, such as Btrfs send/receive and with SSH, to build wrappers for compression algorithms, and even to provide a REST API.

An overview with a small description of the functionality of each component of the RCS system, displayed in Figure 4.3, follows:

Master Node This node acts both as a controller to the replication system and an interface to interact with a client whether through a CLI or REST API. This node shall reside on an iCBD Administration machine since it must deliver changes made to iMIs to all replicas. It is also responsible for communicating with the Name Server to gather information about which nodes are present on the platform, or what is their status; even instruct the replicate nodes to execute certain operations.

Replica Node Its main task is to maintain the list of subscribed iMIs that are not up-to-date, receive the updates as soon as the Master Node sends them, and store them locally. Upon request, the Replica Node can deliver the list of iMIs that are locally stored and their version numbers, and subscribe (or unsubscribe) for new IMIs.

Name Server This service lives in the same machine as the Master Node, holds records about nodes in the replication system, in a phone book type simple database. Nodes register themselves in the name server during the startup process (and leave on shutdown) and can, at any moment, query about the location of other nodes.

Keep Alive It's a Master Node thread that periodically checks if Replica Nodes are still operating correctly. When it identifies that a replica node is no longer responding, it immediately sends a request to the for the removal of the dead node from the Name Server's directory.

Image Repository This module is a custom-made data structure that holds a (large) set of iCBD Snapshot objects in a key:value store. In addition to storing these objects, it has an interface that provides quick answers to queries that ask which iMIs are stored in the node's repository. Every node in the platform (i.e. Master or Replica) must necessarily hold one repository.

All the previously described components interact with a number of “objects”, so it is not a surprise that a sizeable amount of code that we have created has been packed into a number of libraries:

Btrfs Lib The Btrfs library holds two classes: the first one, called `Btrfs Tool`, is a Python wrapper for `btrfs-progs`, described in section 4.2.1; the other class, designated `BtrfsFsCheck` implements functions that validate if a given path transverses a Btrfs

filesystem and, if it does, verifies if in that path a subvolume also exists. Additionally, a method is provided to discover all snapshots in a directory.

Compression Lib Since multiple compression algorithms are used, it makes sense to create a library that encapsulates multiple wrappers, one for each algorithm; these wrappers only contain code that provides compression and decompression of data streams, no other operations are present.

Serialiser Lib Some communication operations between nodes require the transmission of objects; therefore a library containing serialisation and deserialisation methods for those objects has been implemented.

SSH Lib This library implements a wrapper for the SSH command, allowing the creation of tunnels so that data can be funnelled through a secure connection between nodes.

REST API Lib To comply with one of the objectives of the replication module, a REST API should be provided. That is precisely what this library does, providing the endpoints to interact with the system, and enabling an easy way to expand that interaction to other platform modules.

The libraries we created to implemented the common set of functionalities required for the replication module, do require more libraries, implemented by the Python community. An inventory with the library dependencies is presented in Listing 1. These are necessary to handle communication between nodes, algorithms for data compression, and secure data transmission; the most relevant ones are described through the remaining text in this section.

4.2.3 Communications between nodes

To coordinate the multiple modules and their activities, an abstraction of a network-shared communication channel must be supported. The remote procedure call (RPC) was chosen to support the inter-process communication, allowing a procedure running on a system to invoke an operation in a process running in a different location, most likely on a remote system.

As seen in figure 4.3, multiple processes are running in different machines any given time, and these processes need to continually send and receive information: operations that must be executed, metadata updates, monitoring if a process is compliant with its expected behaviour or is in a faulty state, etc. Managing nodes is just the right case for the Pyro 4 library, one that gives an holistic view of the system and allows triggering operations in a node.

Pyro4 Library Pyro4 [29] is a library that enables the development of Python applications where objects can talk to each other over the network through the use of RPCs. It is

```
[[source]]
url = "https://pypi.python.org/simple"
verify_ssl = true
name = "pypi"

[packages]
"pyro4" = "==4.62"
serpent = "==1.23"
"py-lz4framed" = "==0.10.0"
python-snappy = "==0.5.1"
Sphinx = "==1.6.6"
sphinx_rtd_theme = "==0.2.4"
flask = "==0.12.2"
Flask-Jsonpify = "==1.5.0"
Flask-RESTful = "==0.3.6"

[dev-packages]

[requires]
python_version = "3.6"
```

Listing 1: Dependences of the iCBD-Replication module bundled in a Pipfile

designed to be very easy to use and integrate in projects while having a considerable flexibility. This library can be imagined as a glue that easily integrates various components of a heterogeneous system.

Some Pyro4 core features are used in the iCBD replication module including (but not limited to):

Proxy This object acts as a substitute for the real one, intercepting the calls to a given method of that object. Then, through the Pyro library, the call is sent to the actual object - one that will probably reside in a remote machine – and will return the resulting data (very useful, considering that the function that performs the call does not need to know if it is dealing with a local or remote object).

Pyro object A Pyro object is a regular Python object that goes through a registration process with Pyro in order to facilitate remote access to it. Objects are written just as any other piece of code, but the fact that Pyro knows their existence allows other programs to place calls.

Pyro daemon This component listens for remote method calls done to a proxy, dispatches them to the real object, collects the result of the call, and returns it to the caller.

Name Server It keeps track of the object's actual locations in the network so that they can move around freely and transparently. Similarly to a yellow-pages book, provides a way to lookup objects based on metadata tags.

Automatic reconnecting Provides an automatic retry mechanism to handle the fault that arises when a client (in our case a Replica Node) becomes disconnected from the server (Master Node) as a result of a server crash or communications error.

Secure communication Pyro, in itself, does not encrypt by default the data it sends over the network. Still, Pyro RPCs communications can travel over a secure network (VPN, SSL/SSH tunnel) where the encryption is performed outside the library. Alternatively, it is also possible to enable SSL/TLS in the Pyro library itself, securing all communications with custom cert files, private keys, and passwords.

Serialisation Pyro supports the transformation of objects into streams of bytes that flow over the network to a receiver that reconstructs them back into the original format. This process is essential to ensure the delivery of all data that remote method calls receive as arguments, as well as the corresponding responses they return.

TCP Sockets and Secure Shell Protocol (SSH) Coordination of system activities is only a part of the work that “loads” the network; the other, and more important part, is carrying large volumes of data (as a result of transferring GB-sized iMIs) to perform the replication tasks that keep VM images consistent across RCS nodes. The Pyro4 library allows secure communications, but only for method calls (arguments and responses) within replication nodes.

The delivery process of iMIs throughout nodes follows one out of two principles: in the first scenario, we consider the case where the iMI does not leave the same trusted local network (i.e. communications within the walls of one organisation); the second covers the transport of data across external networks, including the Internet.

When discussing intranet environments, it’s safe to assume that there are some security measures already in place (e.g. VLANs) so, in this regard, we assume that data security is already catered for. That allows us to use a simple Stream Socket [21], which does provide a connection-oriented flow of data with error detection, in our case implemented on top of TCP. This option, when paired with non-encrypted communications, delivers the best performance possible for the transfer of an iMI.

In the second case, which involves data travelling through external networks, an extension of the previous solution is employed: we used the same type of socket, but transport data through an SSH tunnel deployed between nodes.

This, in addition to solving the issue of ensuring data security in the transferal process, has the benefit of being a modular solution that allows future changes in the way data is encrypted without needing significant modifications to the code base. But, while we do not believe that this is a perfect security model, and there is room for improvement, we will not pursue that avenue because this is not the focal point of this work. However, the current solution does provide the level of security we deemed enough to conduct functional tests linking geographically separated data centres.

Data Compression As noted in the section where requirements were discussed, our implementation should aim for a reduction in the bandwidth used by operations in the iCBD platform, and that includes the replication of iMIs. Part of it is already addressed in the Storage Layer since the images, by default, are transparently stored in Btrfs compressed with zlib [31]. However, the replication process using the Btrfs send and receive, as explained in section 4.2.1, does not send an iMI itself, but an “instruction” stream (which includes the data to be transferred) which, in itself, is an excellent candidate to compression.

Given the design of the send/receive features, is unthinkable to hold in memory all the stream waiting to be compressed, or store that information in a file, compress it, and then send it, without creating a huge bottleneck and introducing a delay on the replication process. To expedite the process of transmitting a compressed stream immediately, only compression algorithms that provide a framing format (i.e. allow decompressing without having to hold the entire stream in memory) were chosen.

In this work, we included three algorithms that implement the framing format feature and were found to be widely used, while maintaining a modular code base in order to support the future inclusion of other algorithms.

LZ4 is a lossless data compression algorithm that belongs to the LZ77 family [64] of byte-oriented compression schemes and is focused on maximizing compression and decompression speeds. Its reference implementation is in C and was initially implemented by Yann Collet. There are ports and bindings in various languages such as Java, C#, Python, and Go, among others. In this work, we use a multithreaded Python version developed by Iotic Labs called *py-lz4framed* [28].

zlib is a widely used, and kind of a *de facto* standard, library of lossless data compression that uses an abstraction of the DEFLATE compression algorithm (also a variation of LZ77). The algorithm version written by Jean-loup Gailly and Mark Adler provides good compression on a wide variety of data sets and environments with the minimal use of system resources [1]. Written in C, it can be found in a wide diversity of platforms: in the Linux Kernel in multiple modules, and in multimedia libraries, databases, version control systems, and others. In the replication module, we use the zlib library [17] included in Python, which then provides an interface to the zlib C library.

Snappy is a compression / decompression library, created by Google [19], that contrary to other algorithms, strives for very high speeds at reasonable compression rates, not maximum compression. The library is written in C++ but has several bindings for the most popular languages. In order to interface with Python, we used the Python binding [43] for the snappy C++ compression library provided by Andrés Moreira.

4.2.4 Name Server

In a distributed systems environment, nodes need to know how to communicate with each other, uniquely identify themselves and be able to refer to their locations. The mechanism that addresses this problem is commonly referred to as Naming [56].

The iCBD Replication module implements a Naming Server, where each node is identified by a tuple with three elements: Node Name, Node URI, and Tag. Tuples are registered in the name server and operation include locating a node by its name, or retrieving a set of nodes that are marked with the same tag.

The name server is a module that consists of a continuously running thread and a local SQLite database. It uses the aforementioned Pyro4 Name Server, but instead of being launched from a console, it leverages the “launch on your code” feature provided by the library to seamlessly integrate with the remaining modules and starts up together with other modules of the Master Node. The name server initialisation process, using this feature can be seen in Listing 2.

Consider the scenario where a node wants to contact another node and does not have its location: a request (which includes the name of the target node) must be made to the name server, expecting in return a URI for the target node. If the requesting node already knows the location (IP and Port) of the name server, it directly addresses it; however, if the node does not know how to contact the name server, it resorts to a simple UDP network broadcast to locate it.

Methods in the Name Server API The Pyro Name Server presents an extensive API but, for the purpose of our work, only the subset presented below is used:

`locateNS()` Get a proxy for a name server somewhere in the network.

`register()` Enrol an object in the name server, associating the URI with a logical name.

`list()` List all objects registered in the name server; the results will be filtered if a prefix is provided.

`lookup()` Looks for a single name registration and returns the corresponding URI.

`remove()` Removes an entry, created by registering an object with the exact given name, from the name server.

4.2.5 Image Repository

Each Replica Node in the platform can subscribe to an independent set of iMIs that will be replicated to its local storage, with the Master Node holding the entire collection. To represent this relation between nodes and to facilitate the process of knowing which image is present in each node, we implemented an Image Repository.

```
class NameServer(Thread):

    def __init__(self, config):
        # Thread configs
        Thread.__init__(self, name="Thread-NameServer")
        self.ns_ip = config["ip"]
        self.ns_port = config["port"]
        self.ns_db = config["dbFile"]

        # Pyro name server
        self.nameserver_uri,
        self.nameserver_daemon,
        self.broadcast_server = Pyro4.naming.startNS(host=self.ns_ip,
                                                       port=self.ns_port,
                                                       storage=self.ns_db)

        self.nameserver_daemon.combine(self.broadcast_server)

    def run(self):
        # This is triggered in the thread.start() call
        try:
            self.nameserver_daemon.requestLoop()
        finally:
            # clean up
            self.broadcast_server.close()
            self.nameserver_daemon.close()
```

Listing 2: Starting procedure of a Name Server

The Image Repository sub-module is present in every node (Master and Replicas) and plays a central role in the replication process, not only because it acts as a backbone for the subscription of images, but also because it tracks all iMI versions available in the platform in a way similar to that of a versioning system. As described before, the iCBD platform stores multiple versions of one iMI as snapshots, that materialise as directories in the local filesystem. The information stored by the Image Repository is backed in persistent storage in the form of an SQLite database, similarly to what happens in the Name Server.

The interface that the Image Repository provides is very simple, and consists of a handful of mutator methods (get and set functions) that populate one main data structure, based on the Python built-in Dictionary, thus providing an unordered set of key:value pairs, where the key is the name of the iMI and the value is a List of several *icbdSnapshot* objects, one for each version.

iCBD Snapshot Object Structure (iMI) Inside the replication module the iMI, as presented in Section 3.2.1, is treated as a first-class citizen, being represented by the class *icbdSnapshot*. This object stores the relevant metadata and properties of an iMI that are essential to unequivocally identify the multiple images present in the system unequivocally; but it does not hold actual data.

In that sense, from this lightweight object, we can get hold of: the name of the iMI, its version number, the full path to the VM files in the filesystem, the location of the boot package associated with that particular version, and the configuration file for the iSCSI target.

Since the data stored in this object is appended at creation and is immutable, the object only provides get functions to retrieve its values. Given that all the relevant data is stored locally in a node (i.e. the actual VM file, the boot package, and the iSCSI configuration files) the *icbdSnapshot* object only needs to maintain paths to that data with regard to the local filesystem, leading to a clean and straightforward interface that can be seen in Listing 3.

```
class icbdSnapshot(object):
    def __init__(self, mount_point: str,
                 image_name: str,
                 snapshot_number: str,
                 creation_time: float,
                 icbd_boot_package_path: str,
                 iscsi_target_folder: str):

        # Path to the FS where the VM Files are stored
        self.mount_point = mount_point
        # Name of the iMI
        self.image_name = image_name
        # Version number
        self.snapshot_number = snapshot_number
        # Moment the iMI was added to the platform
        self.creation_time = creation_time

        # iMI Boot Package
        self.icbd_boot_package_path = icbd_boot_package_path

        # iMI iSCSI target
        self.iscsi_target_folder = iscsi_target_folder
        self.iscsi_target_name = "{}-{}_flat.conf".format(self.image_name,
                                                       self.snapshot_number)
```

Listing 3: Example of the information stored in the *icbdSnapshot* object.

4.2.6 Master Node

The architecture and design of the replication process dictate that managing the subscription of iMIs, disseminating new versions and, finally, providing an interface to interact with these services is fundamental.

Given those requirements, the Master Node resides in an iCBD Administration Machine allowing it to hold a global view of all components of the system and a holistic view of the state of the platform (i.e., identify all the nodes present in the platform, list all iMIs in catalogue, maintain a list of all relations between iMIs and nodes - the subscriptions).

And, furthermore, the Master Node also acts as a gateway, providing two methods to interface with the platform: a Command Line Interface (CLI) and an REST API.

Besides having a central role in managing and overseeing the different aspects of the replication platform architecture, the Master Node holds the responsibility of sending new versions of an iMI as soon as they are created, using the Btrfs Incremental Backup feature (in this case, the send operation).

Sending a Snapshot to a Replica Node (Cache Server) The overall process follows these steps: when the task of administrating an iMI is finished, the Master Node is notified that a new version (of that iMI) is available; a new entry for that version is then created and stored in the local Image Repository; afterwards, the main replication procedure starts.

The replication procedure proceeds as follows: first, the list of nodes that have subscribed to that iMI is gathered; then one obtains the last version available in the Replica's Image Repository and that "value" will be used to determine if the new version can be sent immediately, or if it is necessary to transfer some intermediate versions. In any case, only the differences between versions are sent, not the whole iMI. Assuming that only the last delta (the most recent changes) will be shipped, it is now necessary to decide whether the transfer will occur using a plain or encrypted communication channel and/or whether some compression algorithm will be applied to the data before being sent. This information is also conveyed to the receiving side so that it is ready to accept the data.

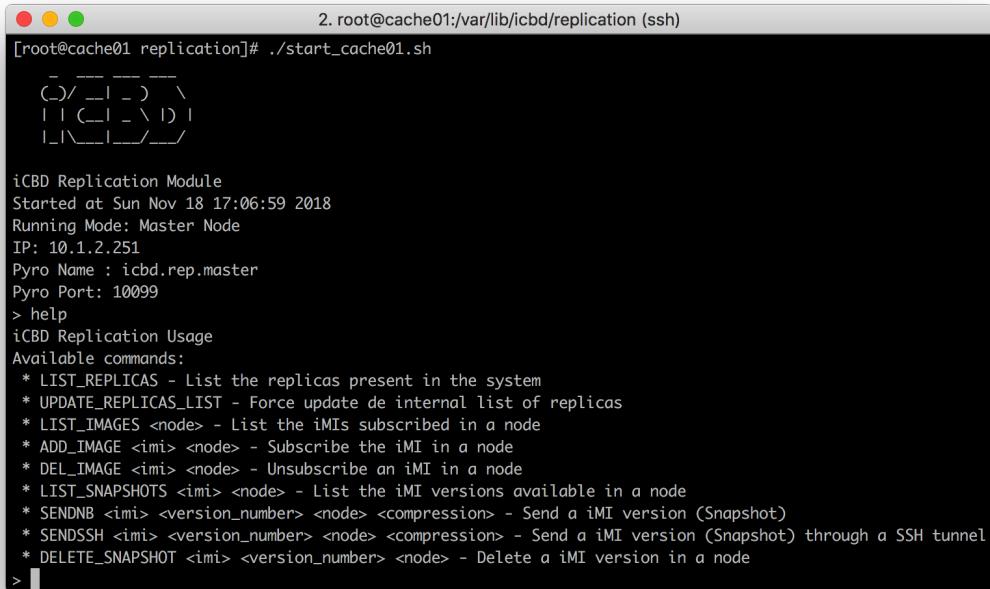
Only after completion of the above-described process, will the data transfer be carried out, using the btrfsLib, compressionLib and sshLib libraries. The process of receiving an IMI can be found in Section 4.2.7.

Keep Alive When the Pyro4 platform was presented, we mentioned that this library allows the automatic reconnection of clients to the Master Node. However, the opposite is not provided, i.e., in case of failure of a Replica Node, the Name Server is not automatically informed of that failure; in fact, this event would only be noticed when a connection with that node was attempted and failed. Since we want the Master Node view to be always consistent with the status of the platform, it is essential that the Name Server is always up-to-date; so, we implemented this module.

The Keep Alive module is started along with the Master Node and runs its own thread, making the execution flow independent of any other sub-module (as with the Name Server). Its main task is to verify the activity status of all Replica Nodes indexed by the Name Server, in a quite simple manner: it gathers the list of all Replica Nodes and, with a period of about ten seconds, each node is sent a message and must deliver a response. If there is no response, two further attempts to contact that node are performed, and if those fail too, it is assumed that something wrong happened and that node is declared inactive. Then, the Name Server is notified that a node entered a failed state, and should be excluded from the “database”.

4.2.6.1 CLI Interface

One of the methods to interact with the iCBD replication platform is through a Command Line Interface provided by the Master Node; the CLI is nothing more than a program that is started on a terminal window and recognises a simple vocabulary that includes a few verbs (command words), arguments and options, executes them, and returns its result.



```

2. root@cache01:/var/lib/icbd/replication (ssh)
[root@cache01 replication]# ./start_cache01.sh
   _/---_ \
  | |(_|_ \_) |
  |_\|__|_/_\|_/
iCBD Replication Module
Started at Sun Nov 18 17:06:59 2018
Running Mode: Master Node
IP: 10.1.2.251
Pyro Name : icbd.rep.master
Pyro Port: 10099
> help
iCBD Replication Usage
Available commands:
* LIST_REPLICAS - List the replicas present in the system
* UPDATE_REPLICAS_LIST - Force update de internal list of replicas
* LIST_IMAGES <node> - List the iMIs subscribed in a node
* ADD_IMAGE <imi> <node> - Subscribe the iMI in a node
* DEL_IMAGE <imi> <node> - Unsubscribe an iMI in a node
* LIST_SNAPSHOTS <imi> <node> - List the iMI versions available in a node
* SENDNB <imi> <version_number> <node> <compression> - Send a iMI version (Snapshot)
* SENDSSH <imi> <version_number> <node> <compression> - Send a iMI version (Snapshot) through a SSH tunnel
* DELETE_SNAPSHOT <imi> <version_number> <node> - Delete a iMI version in a node
> 

```

Figure 4.4: iCBD Replication Module help output

Following we demonstrate the functions provided by this interface (the help output of the CLI is exhibited in Figure 4.4) and the effects produced on the platform:

List Replicas - At any time it is possible to consult which nodes are registered in the platform, this command allows to list the replicas registered in the Name Server and indicates which URI is used to make a connection.

Force Update Name Server - As previously explained, when a replica node stops responding, that node is deleted from the records held by the Name Server. However, this process may not be immediate because of the timeout implemented. So this feature forces an update to the Name Server list by contacting all the nodes and determining if they are working correctly.

List Subscribed iMIs - This command receives as a parameter a replica node and shows a list of which iMIs that node is interested in receiving. It should be noted that a replica node may not subscribe to an iMI but still make it available to its client (was previously subscribed and the data was not deleted), it just will not be receiving new versions as they are being produced.

Subscribe iMI - Like the previous operation, this receives some arguments (a replica node and an iMI), then, registers the interest of the replica node in a given iMI. After this procedure, this node will be able to receive versions of this iMI.

Unsubscribe iMI - When a replica node ceases to be interested in a given image present on the platform, this operation marks that new versions of the iMI should not be transferred to that node. However, all versions that have already been sent persist on the node and in order to be deleted them an appropriated operation must be used.

List iMI available versions - It is usual for a given node to contain multiple versions of an iMI (for example, the Master Node contains all versions of all iMIs that can be distributed). Thus, given an iMI, this operation allows the listing of which versions a node stores.

Send iMI Snapshot - Possibly the most significant operation in this module. It is responsible for sending the respective versions of an iMI to the intended node. Always verifying which versions are present on the target node since only the differences between versions should be sent. This command also supports the application of a compression algorithm from those provided by the platform, since it may be the case of transferring a version for the first time with a very significant data volume, or the changes between versions possess a high compression rate thus making the compression of these data advantageous.

Send iMI Snapshot Secure Connection (SSH) - This functionality is similar to the one presented above. In particular case, they share a large portion of the code, because they carry out the same operations. They only differ in the method of sending the data, which in this instance are transmitted in an encrypted fashion through an SSH tunnel. This functionality is sure to add some overhead to the transfer process, but the encryption of the data is essential in situations where the nodes are in separate networks, where there is no control wheresoever to the data security.

Delete iMI version - Finally, it is necessary to provide a way to delete versions of a given IMI in a node. Either because no longer is desired to make an IMI available or for reasons of proper management the storage space on a replica node. It is important to note that because of the way different versions of iMIs are stored in the platform, deleting older versions may not result in a space release equal to the size of the full iMI, since newer versions probably will still need this data.

4.2.6.2 REST API

In order to complement the Command-Line Interface previously presented and creating a more straightforward, more ubiquitous way of interacting with the replication platform, a Rest API has been introduced. Aiming to provide the same functionalities as the CLI but trying to create the roots of a component that deals well with platform scaling and the introduction of new features or components.

In order to integrate this component with the remaining replication platform, we employ one of the most used frameworks for creating web platforms in Python, the Flask micro-framework [49].

Flask Started as an April's Fool's Day joke to become the second most popular web development frameworks. Flask is a Python micro web framework designed with simplicity in mind, enabling quick deployment of applications and at the same time providing the ability to scale for complex environments. Such library enables the development of web applications without having to worry with more low-level aspects like network protocols and thread management. This framework began its development in 2010 by Armin Ronacher as a wrapper of two of his libraries: Werkzeug [51] and Jinja [50].

Our use of this framework has focused only on its ability to quickly provide an environment for creating a REST API and connecting it with the rest of the replication platform. Next, in Listing 4, we present the endpoints through which it is possible to interact with a master node.

4.2.7 Replica Node

The replica node introduces a lightweight module that is responsible for facilitating the process of transferring and updating the iMIs that are closest to the clients. This module responds to the question of how to simplify the process of making available iMIs closer to the client. Complementing the remaining modules of the iCBD platform, here the focus is on implementing the logic of receiving snapshots, as well as providing a way to manage which iMIs are subscribed with their different versions. With these features, we have all the components to build a cache server, something that will be explained in detail in the section 4.3.

```
GET /api/replicas - list all Replicas in the system  
GET /api/replicas/{replica}/imis - list of the iMIs present in a Replica  
GET /api/replicas/{replica}/imis/subscribe/{imi} - Replica subscribe to iMI  
GET /api/replicas/{replica}/imis/unsubscribe/{imi} - Replica unsubscribe to iMI  
GET /api/replicas/{replica}/imis/{imi}/versions - list the versions of iMI present  
in Replica  
GET /api/replicas/{replica}/imis/{imi}/versions/{version}/delete - delete a ver-  
sion of iMI in Replica  
GET /api/master/imis/ - list the iMIs present in Master  
GET /api/master/imis/{imi}/versions - list versions of iMIs present in Master  
GET /api/master/send?imi={imi}&version={version}&replica={replica} - send ver-  
sion of iMI to Replica
```

Listing 4: iCBD-Replication REST API Route Mapping

Contrasting with the Master Node, it is not possible to interact directly with a replica; all operations will always be conducted through a Master who then is in charge of communicating with the Replica, asking him to perform those actions. This fact is more than an architectural design choice, this way we meet one of the requirements that define that a cache server should be as light as possible leaving the platform management element to a centralised location not needing to know anything concerning the overall platform state. However, there are parts in common. Similarly to the Master Node one of the components present is an Image Repository, which in this case, manages locally the iMIs and respective versions.

Receiving a Snapshot By far, this functionality is the reason for the existence of this module. The process of receiving a version of an iMI is complementary to the send process explained in Section 4.2.6 even though much more straightforward. As explained, the `send()` operation needs some computation resources since it has to calculate all the differences between versions to transfer, and after that step create a stream of operations that when executed recreate precisely the differences between versions. So, on the receiving side of this stream (in this case the Replica Node), the `receive()` operation only is only required to receive the stream, decode the operations to administer to the file system and execute them.

Documentation for all this project was generated using a tool called Sphinx [10] and can be consulted in Annex I.

4.3 Deploying an iCBD Platform with a Cache Server

Once the process of creating a mechanism to support the replication of iMIs has been completed, we have reached a stage where we must tackle the set of problems that may arise when supporting a large number of clients. A short list is: limited bandwidth between the central repository and distant (in terms of latency, but also bandwidth) workstations; high latencies and jitter resulting from network congestion events and/or configuration errors in the network equipment. We believe that bringing the iMIs closer to the workstations is a way to solve all these problems at once.

When our work started, there was already an iCBD infrastructure in place at DI-FCT/NOVA; however, all iCBD support services were deployed in a single VM, with limited resources (when we took into account that the infrastructure had a lot more resources) and tests were run on a couple of VMs that were used as a (virtual) replacement for the user's physical workstations. And the software versions were both quite old, when compared with the iCBD development infrastructure held at SolidNetworks, and missing important features that were then available at the development site.

Those limitations originated from the fact that iCBD project had no dedicated infrastructure, it was sharing the same already scarce resources with other research projects and services at DI. Fortunately, that situation changed with the acquisition of new equipment dedicated solely to this project, and that created the perfect opportunity to re-evaluate the architecture of the iCBD services and carry out a fresh installation of the whole platform.

4.3.1 The iCBD infrastructure at DI-FCT NOVA

The core of the iCBD infrastructure at DI-FCT NOVA is a two-node cluster based on HPE ProLiant DL380 Gen9 servers interconnected via an HPE Flexfabric 5700 managed switch with 10Gbps links with external storage provided by an HPE MSA 2040 SAN Storage Disk Array. For the "remote" nodes, i.e., the replication and cache servers, the project proposal that was submitted for funding had low-end/low-cost servers in mind; in our tests, a desktop PC that was disposed from another research project was reconditioned, and we upgraded the amount of RAM and added a second hard disk.

Finally, the workstation/client testbed was provided by two student laboratories at DI (Labs. 110 and 112), each containing 15 modern PCs (CPU - Intel Core i3-7100 @ 3.90GHz; RAM - 8 GB; Gigabit Ethernet). An important feature was the i3 CPU, which supports Intel VT and is able to run hypervisors.

The detailed specifications of all these components can be found in the tables 4.1, 4.2 and 4.5.

<i>CPU</i>	2x Intel Xeon E5-2670 v3 @ 2.30GHz
<i>Memory</i>	128 GB
<i>Controller Type</i>	12Gb/s SAS
<i>Ethernet</i>	2 ports at 10 Gbps plus 4 ports at 1 Gbps
<i>Hypervisor</i>	VMware ESXi, 6.5.0, 4564106

Table 4.1: Specifications of one HP ProLiant DL380 Gen9 host

<i>Controllers</i>	2 MSA 2040 SAS
<i>Total Capacity</i>	7.2 TB
<i>Disk</i> s	12 HP SAS 600GB 10k Rpm
<i>Host interface</i>	8 12Gb/sec SAS ports (4 per controller)
<i>Ethernet</i>	2 ports at 1 Gbps (1 per controller)

Table 4.2: Specifications of the HPE MSA 2040 SAN Storage

iCBD Networking iCBD must be able to coexist with other services and be integrated into existing networks; therefore, we studied all types of traffic generated by the platform in order to be able to segregate it into different logical (or physical, if the need arises) networks thus preventing it from “interfering” with other services in the organisation. At the topmost level we can subdivide the traffic in two groups: internal, restricted to the platform, which is generated by the different iCBD services when they communicate between them; and external, which can be further subdivided into general Internet access, intra-net traffic, between the core platform and remote servers or workstation clients in the labs – for example, for iMI transfer.

The iCBD core cluster runs the VMware vSphere suite, which provides advanced network virtualisation features. One of those is the Distributed vSwitch (DVS) which is a single virtual switch that spans all (or a subset of) nodes in the cluster and acts as a single point of administration for the creation of “port groups” that share a common set of characteristics (such as VLAN ID), and to whom VMs connect.

The iCBD infrastructure uses two DVSs:

DI DVS - This virtual switch, dedicated to external traffic, holds five port groups: two of them handling traffic to the two student labs, and the rest supporting the (logical) networks used by various services of the department with differentiating levels of access (students, teachers, public).

iCBD DVS - This virtual switch, dedicated to internal cluster traffic, has port groups that differentiate the various types of traffic: management; administration of iMIs; monitoring (of traffic generated in platform tests); and, finally, traffic for the Replication and Caching System.

DI Distributed VSwitch		iCBD Distributed VSwitch	
Port Group	VLAN	Port Group	VLAN
DMZ-PRIV-DI	DMZ-PRIV-DI	iCBD-Adm-Net	VMWARE_VMOTION_DI
DMZ-PUB-DI	DMZ-PUB-DI	iCBD-Ceph	VMWARE_VMOTION_DI
LAB-DI-110	LAB-DI-110	iCBD-Net	VMWARE_VMOTION_DI
LAB-DI-112	LAB-DI-112	iCBD-Rep	VMWARE_FT_DI
R-ENSINO-PRIV-DI	R-ENSINO-PRIV-DI		

Table 4.3: Specifications of all Networks

Table 4.3 lists the relationship between the VDS portgroups and the FCT/NOVA VLANs (which are managed by an external entity – the Divisão de Infraestruturas Informáticas).

4.3.2 Roles in the Platform

As previously reported, from the beginning of the project, the entire platform was supported by a single VM that centralised all the services – and that is still the case in the SolidNetworks site. But, taking advantage of the new hardware, we set out to distribute the different platform services to distinct servers (physical and virtual), using the notion of roles. The current version has the following roles/servers:

iCBD-imgs This server can be considered the core of the iCBD platform, as it fulfils three iMI roles: administration (it handles the iMI administration process), storage of iMIs (in the platform storage backends), and the deployment of iMIs (to workstations). With the creation of the replication system, one more service was added to this server, since it is here that the Master Node, which manages the replication of iMIs, will run.

For the deployment of the iCBD-imgs role, a VM with 4 vCPUs, 32GB vRAM and 2 Hard Disks (OS and Data) was created in the iCBD cluster.

iCBD-rw This server's key role is to make temporary read/write space available to clients, during the boot process; clients see (mount) it as a directory and, while they are running, changes that both users and system apply are saved, but only for the duration of the session; once the session is over, that data is deleted.

One of the reasons for separating this functionality from those provided by the iCBD-imgs machine was to offer a simple way to visualise the load that results from multiple clients booting iMIs at the same time, separating that usage from reads and writes that occur during “normal” operation. Since the server's only task is the provision of iSCSI and NFS servers that offer r/w space, we think that we can lower the RAM usage when compared with iCBD-imgs and deploy a VM with 4 vCPUs, 8GB vRAM and 2 Hard Disks (OS and Data).

	vCPU	vRam	Hard Disks	Interfaces	OS
<i>iCBD-imgs</i>	4	32 GB	16 GB + 600 GB	5	CentOS 7
<i>iCBD-rw</i>	4	8 GB	16 GB + 300 GB	4	CentOS 7
<i>iCBD-home</i>	4	8 GB	16 GB + 100 GB	4	CentOS 7
<i>iCBD-cache</i>	4	32 GB	16 GB + 600 GB	2	CentOS 7
<i>iCBD-client</i>	4	8 GB	Diskless	1	Network Boot

Table 4.4: Specifications of the virtual hardware of the iCBD machines

As the functionality of this machine is only the provision of iSCSI and NFS servers for accessing r/w space its specifications may be a bit more conservative with a VM boasting 4 vCPUs, 8GB vRAM and 2 Hard Disks (OS and Data).

iCBD-home This is an optional role, for an NFS-based service that handles access to user home directories, which makes sense in an environment where a large community uses Linux. The iCBD-home server will either host the storage itself or consume it from a storage backend; in any case it will hold the user’s home directories and export them to the user’s workstations in a secure way, in a straightforward process: each user has a home directory under the iCBD-home server’s /home; then, when the user boots his/her workstation from a Linux iMI, that directory is exported by NFS and mounted in the workstation’s /home, thus enabling the user to log in and access its contents. The iCBD-home could also, in theory, act, in a Windows environment, as a gateway to a CIFS server; however, support for this type of “remote storage” for Windows clients was not implemented in our project.

The specifications for the iCBD-home VM are very similar to those of iCBD-rw, with the exception of the size of the second, “data”, disk - which could be zero, if that storage was provided by an external storage server, to the amount deemed suitable for the particular iCBD installation.

iCBD-cache This was the service (a.k.a. Cache Server) that we have architected, designed, implemented and deployed in this thesis. From the client’s point-of-view, it is indistinguishable from the iCBD-imgs service that provisions iMIs to workstations but, with the introduction of RCS, each Cache Server also runs the Replica Node service (introduced in Section 4.2.7), aiming to reduce the latency and increase the transmission rate between the image server and the workstations, thus improving the user’s experience. It may be implemented, as it was the case with the other roles, on physical or virtualised hardware.

On the DI-FCT/NOVA site, two types of cache servers were set up: a virtual machine, because it was easier to deploy and test the correctness of its operation; and, later on, a physical server that was connected directly to one of the students’ labs and was responsible for delivering the iMIs to that lab’s workstations. Both configurations can be seen in the tables 4.4 and 4.5, respectively.

iCBD-admin_iMI This is a special role created specifically for the administration of iMIs.

The process of administering an iMI is triggered and managed by scripts that run within the iCBD-imgs server, but since administration always involves the need to run a VM based on the iMI we want to manage, this process can be carried out in two different ways: in the iCBD-imgs server itself, in nested virtualisation mode; or, running the iCBD-admin_iMI VM as yet another VM running in the iCBD cluster.

Nested virtualisation mode Here the iCBD-admin_iMI VM is executed under a VMware Workstation (or Player) Type II hypervisor, i.e., an hypervisor that executes as a OS process in a CentOS (our default choice) or another suitable hosting OS. Running in nested virtualisation mode has a moderate-to-high decrease in performance.

Standard virtualisation mode Here the iCBD-admin_iMI VM is executed directly on the VMware vSphere Type I (a.k.a. native, or bare-metal) hypervisor, i.e., an hypervisor that executes directly on the server's hardware.

Whatever our choice is, the iCBD-admin_iMI VM is created dynamically by the administration process and works in a similar way to a client, with a difference: changes made to the IMI may be committed and used to create a new version of that iMI.

iCBD-client The platform client is the simplest of roles. Again, there are two cases, depending on whether the client is a physical workstation or a VM: we can create a diskless virtual machine, and connect it to a network where an image server (iCBD-imgs or iCBD-cache) is located (visible) and boot the VM using a network boot process – the result is an iMI being provided to that to that VM, the TFTP will transfer the kernel,..., (as was largely described in section 3.2.2) and the client will end running the chosen OS. Naturally, the same process can be used for a workstation provided that the physical network has connectivity to the appropriate iCBD networks. Furthermore, other ways to boot an iMI on a workstation, such as creating a bootable USB drive that connects the workstation to an image server, without using DHCP or PXE, are possible.

<i>CPU</i>	Intel Core i5-650 @ 3.20GHz
<i>Memory</i>	12 GB
<i>Storage</i>	2x SATA 80 GB + SATA 160 GB
<i>Ethernet</i>	2 ports at 1 Gbps
<i>OS</i>	CentOS 7 3.10.0-514

Table 4.5: Specifications of the Physical Cache Server

4.3.3 Installing iCBD Core Services

As one may deduce from the number of roles described above and the complexity of their interactions, deploying the iCBD platform (services), even with the enormous benefits brought by virtualisation, is not a trivial task. First, the networking infrastructure connections must be made, and then the configuration must be deployed. Deploying the network configuration is a slow process because it involves many interactions with the Faculty group that is responsible for networking infrastructures at the university campus. The VLANs, security/firewall policies, etc., all must be defined and “negotiated”, as the iCBD switches must be managed by that same group (that is understandable because if they were managed by any other group – ourselves included – the opportunity for “breaking the rules” / “violating the policies” would be there). New policies had to be defined so that the iCBD servers could “tap” into the student’s labs, for PXE booting, TFTP and/or HTTP image transfer, and NFS or iSCSI mounting all were transparently handled without jeopardising the labs normal operation.

The installation process was carried out in three phases. In the first phase, VMs for the various services (roles) - iCBD-imgs, iCBD-rw, and iCBD-home – were created from a vSphere template with a minimal CentOS 7 installation. Then, for each VM, the CentOS packages and other software that was necessary to support the role were installed and configured. Finally, some iMIs that were already available in the SolidNetworks site were transferred and prepared to operate in the DI site. At the end of the first phase, VMs posing as workstations could be started inside the cluster and boot the available iMIs.

The creation of multiple virtualised Cache Servers constitutes the second phase. The creation of these VMs was an easy step because the iCBD-imgs was used as a base VM from which the first Cache Server VM was created, through the use of a full cloning procedure. Then, the unnecessary functionalities (with regard to the new role) were removed, and the modules that provide the Replication service were added. This step was crucial to create a test environment for the replication modules, which before this phase, had not been tested with production iMIs.

The last phase was the installation of a single physical Cache Server as close as possible to one of the labs, and that was accomplished by plugging it directly to the switch that interconnected all the lab workstations. So, we successfully reached a point where we had two setups with access to the iCBD platform: one, where the lab’s 15 PCs were able to get their IMIs from a (physical) Cache Server; the other, where the lab’s 15 PCs had to get their iMIs from the iCBD-imgs virtual machine hosted in the cluster.

The process of creating a single VM for the iCBD platform is, obviously, quite cumbersome (despite the short description we gave when discussing the first phase) and with some significant details that must be addressed. So, we have provided in Annex II a document that was produced when the installation process of the iCBD DI platform was carried out. The document provides, we believe, a detailed and clear explanation of all steps needed to create the VM, and then install and configure each iCBD service.

Btrfs bug found in CentOS 7 Kernel As a curiosity, during the process of building the iCBD-imgs VM, we found a bug in a fundamental component of the *coreutils* tool delivered with the CentOS 7 kernel version 3.10.0-693.5.2: the cp command, when used with option `--reflink=always`, failed with the error message “failed to clone ‘someFile’: Operation not supported”. This behaviour was reported to both CentOS and Red Hat and was eventually fixed. A more in-depth description of this process can be found in Annex III.

EVALUATION

This chapter reports the experimental work performed in order to study both the functionality and performance of the Replication and Caching Service. We start by laying out the test plan followed by the results that we collected. We then analyse those results, always trying to co-relate them with other events observed in the platform.

The chapter is divided into the following sections:

Section 5.1 begins by showing how it was applied and what changes were needed to the infrastructure described in the previous chapter, in order to carry out all the measurements that we propose to evaluate.

Section 5.2 overviews the two procedures applied for the evaluation of the Replication and Caching Service, both for functional validation and performance analysis.

Section 5.3 shows how was developed the benchmark for the performance test of the replication module, then presents the results of those tests, and ends with a comparative analysis.

Section 5.4 finally details the performance tests conducted to the inclusion of a cache server in the iCBD platform, taking into account the boot time of the workstations and the provenience of the iMIs.

CPU	Intel Core i3-7100 @ 3.90GHz
Memory	8 GB
Storage	275GB SSD
Ethernet	1 Gbps

Table 5.1: Specifications of the Laboratories Workstations

5.1 Experimental Setup

As discussed in the previous chapter, the DI (Computer Science Department) provided two laboratories (Lab 110 and Lab. 112) fully equipped with fifteen desktop PCs each (the general specifications of those machines can be seen in the table 5.1), for the validation of the caching solution both at the functional and performance levels.

To ensure the correct execution of all the tests we had planned, some adjustments to the iCBD platform were necessary. From the infrastructure point-of-view, we deployed two more virtual cache servers (raising their number to a total of three). From a functional point-of-view, the iCBD-rw and iCBD-home VMs were moved to the same networks (VLANs) of these labs, and their interfaces configured with the appropriate static IPs. Then, a vNIC (Virtual Network Interface Card) of the iCBD-imgs VM was connected to the Lab. 110 VLAN and assigned the appropriate fixed IP. This restructuring also required changes in the iCBD configuration files to allow the lab's workstations to access iMIs. The Physical Cache Server also had one of its NICs configured in the Lab. 112 VLAN, and similar configurations were necessary in order to allow the server to provide iMIs to the lab's workstations.

	FCT NOVA	SolidNetworks (Development)
Servers	2x HPE ProLiant DL380 Gen9	2 x HPE ProLiant DL380 Gen9
Switch	HPE FlexFabric 5700 jg898a	HPE FlexFabric 5700 jg898a
Disk Array	HPE MSA 2040 SAN Storage	N/A - (Storage on the Server)
Networking	10 Gbps (between servers)	10 Gbps (between servers)

Table 5.2: Physical infrastructure of the FCT NOVA and SolidNetworks sites

Finally, two more (but important) aspects should be referred: first, the Physical Cache Server and the Lab. 112 workstations were attached to the same switch, so the traffic flowing between them was internal to the device, whereas all communications between workstations (of the two labs) and the iCBD VMs had to cross a few switches in the faculty's network and therefore may suffer from adverse network conditions that were entirely out of our control; the second aspect is link speeds - all connections are 1 Gbps links, including the physical interfaces of the servers and virtual interfaces of the VMs. A simplistic schematic of all connections can be found in Figure 5.1.

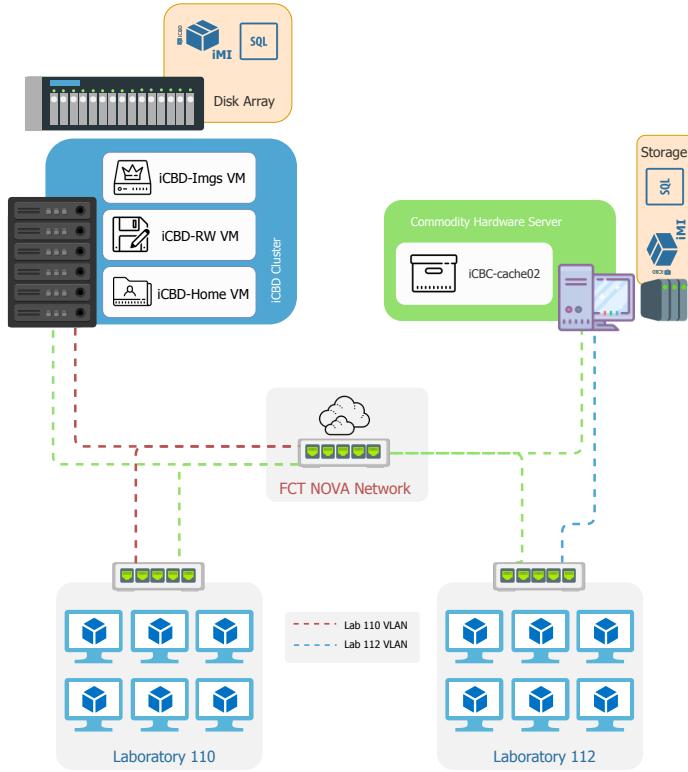


Figure 5.1: iCBD Nodes and Networking Setup

5.2 Metodology

The analysis of the RCS was performed in two distinct moments: in the first moment, we addressed the functional validation of RCS (we covered both components, replication and caching), after being integrated into the iCBD platform - the tests were to assert its correct operation; in the second moment, our focus was on the performance of both components in a production environment.

Functional validation In order to test the functional correctness of the replication module in a multi-node environment, the Master Node was started in the iCBD-imgs VM and three Replica Nodes were also started, one in each Cache Server (virtual: iCBD-cache01 and iCBD-cache03; physical - iCBD-cache02). We observed that the Replica Nodes had registered themselves on the Name Server, as expected, and that the communications between the Master Node and Replicas also performed as expected. Next, were repeatedly carried out two types of tests: one focused on sending a full iMI version (one that was not present in the Replicas' Image Repository), forcing the data to be copied over the network. Furthermore, we wanted to verify that, when the transfer completed, the local Image Repository reflected the addition of the new iMI. This scenario is likely to occur the first time that a replica subscribes to a new iMI.

The second type of test addressed the process of sending iMI versions that were newer than those already available at Replica nodes. This test simulates the case where, after the

administration of an iMI, the new, updated version should be distributed to the Replicas with conservation of bandwidth, i.e., where only the data differences were transferred. At the end of each test, a calculation of an MD5 hash was performed with the `md5sum` tool, in order to ensure that the received data was being reliably transferred and the replica was identical to the original.

Functional testing of Cache Servers was performed with iCBD-cache02, the physical Cache Server, mostly because it was connected directly to one of the labs and thus allowing for immediate testing of a workstation’s iMI boot. Given the degree of integration of the iCBD platform with the remaining network services and policies of FCT NOVA, a considerable iterative process of experimentation was required, tuning some parameters of a few iCBD services until we arrived at a fully functional configuration. In the end, it was confirmed that it was indeed possible to boot the workstations with iMIs delivered by the Cache Server.

Performance Benchmarking In this second phase of our tests, the goal was to ascertain the performance of RCS in a production environment. In the case of the replication module, we compared the results obtained from multiple configurations of our implementation (transfers performed with or without compression and over secure or plain communication channels) and the `rsync` tool; we measured both the time spent on the transfer as well the amount of data transmitted between nodes.

Another important metric that we observed was the time spent on the boot process of a workstation, and we compared the results obtained in the case where the iMI was transferred from the Cache Server against those gathered when it was transferred by the iCBD-imgs VM hosted at the cluster (this one was provided with more resources – vCPUs and vRAM). The time spent on the boot process was computed as the elapsed time between the start of the kernel loading operation, to the moment when the initialisation of all user-space services was finished. The utility that gathered these events was `systemd-analyze`.

Finally, unless otherwise stated, all tests were executed five times; the best and worst results were then removed, and the final result is the average of the remaining values. The results of the benchmark are laid out in the following sections.

5.3 Replication Service Benchmark

Let’s just briefly recall the two tests that we set out to perform: one, focused on sending a full iMI version (one that was not present in the Replicas’ Image Repository), forcing the data to be copied over the network; the other focused on sending iMI versions that were newer than those already available at Replica nodes, which should receive only receive the differences (deltas) associated with the new version.

For these tests, a Linux iMI containing an Ubuntu Desktop 16.04 LTS distribution (with quite a few “extras”, such as OpenOffice) was chosen, and two consecutive versions,

v1 and v2 were used. These versions were created as follows: v1, the base version of this iMI, occupies 38.60GB; we started an administration VM and performed a full update with the apt tool (an `apt-get update` followed by an `apt-get upgrade`), and committed the results to the new version, v2.

Using the btrfs-progs package we issued the command `btrfs filesystem df /path/` to retrieve Btrfs' view about the differences between versions v1 and v2, which the utility reported as being 4.45 GB.

For both test scenarios, we created four different settings for the transfer tests:

Rsync Transfer of an iMI using the rsync tool¹ with the options `-r` (recurse into directories); `-t` (preserve modification times); `-p` (preserve permissions); `-l` (copy symlinks as symlinks) and `-u` (skip files that are newer on the receiver).

iCBD-Rep - I Use the iCBD-Replication platform services to transfer the iMI using the standard Python sockets, and no compression.

iCBD-Rep - II Use the iCBD-Replication platform services to transfer the iMI using the standard Python sockets , with compression using the LZ4 algorithm over the data stream.

iCBD-Rep - III Use the iCBD-Replication platform services to transfer the iMI over an SSH tunnel, without compression.

Sending a complete version of an iMI This test that sends a complete iMI, that is, all its 38.60GB of data; we observed that our iCBD replication module performs similarly on the three tests (I to III), but lags when compared to rsync; the results are shown in Table 5.3. It also shows that the rsync transfer process is faster than our Python-plus-btrfs-send code; however, using rsync has a drawback: after the transfer is complete, we have to use the Btrfs tools to recreate the versioning structure, and that takes time (which we have not measured).

	Time	Data Sent (MB)
<i>Rsync</i>	12m23s	39543
<i>iCBD-Rep - I</i>	17m21s	38947
<i>iCBD-Rep - II</i>	20m35s	35572
<i>iCBD-Rep - III</i>	22m55s	39412

Table 5.3: Time spent and data transmitted on transferring a complete iMI from Master to Replica

The tests also indicate that the IMI is compressible, with savings at around 8.6%. Compression, when applied to a btrfs-send stream, is applied to both data and instructions generated by the send operation.

¹It should be noted that the rsync tool is not aware of a Btrfs subvolume, so the times presented only relate to data transmission, but more operations would be needed to make the iMI functional within the iCBD platform.

Sending only the delta between version of an iMI We now present the results for the test cases where just the differences between the two versions of the iMI were transferred. From the outset, one can see, as expected, a drastic reduction on the amount of data transmitted over the network. The results are shown in Table 5.4.

	Time	Data Sent (MB)
<i>Rsync</i>	10m15s	5964
<i>iCBD-Rep - I</i>	1m47s	4864
<i>iCBD-Rep - II</i>	2m15s	4713
<i>iCBD-Rep - III</i>	2m55s	4902

Table 5.4: Time spent and data transmitted on transferring a delta between v1 and v2 of an iMI from Master to Replica

Our solution using Btrfs send and receive operations shows it to be far superior to rsync’s performance on the same data set. Even in the cases where the compression or cypher options were used, the results did not change dramatically. Here, our conclusion for the staggering difference between rsync and our solution(s) is that rsync takes an enormous amount of time computing the differences (with block-by-block comparisons) and “deciding” on what to send.

5.4 Cache Server Performance Benchmark

With this next benchmark we present, we want to evaluate the behaviour of introducing a Cache Server in a production environment. In order to obtain some interesting metrics, two types of tests were carried out, one scenario in which five workstations are sequentially booted, and the second experiments with the extreme case in which all the machines in a laboratory are connected at the same time, creating a situation known as boot storm. For each scenario, we measured the boot times of each workstation, and with a tool called netdata [57] monitored the state of the server at the time it is serving the iMIs.

In addition to the two scenarios, there are more variables in play. All tests were performed with all links connected at Gigabit speed. Then every single one was repeated with links limited to 100 Mbps. For this to happen, on the tests referring to the Cache Server, the interface that serves the Lab. 112 was configured at this slower speed. As for the VM that serves the Lab. 110, iCBD-imgs, the type of virtual interface employed does not allow the change of its speed but using the Traffic Shaping feature of the Distributed VSwitch, we managed to limit the bandwidth of the entire PortGroup that refers to this laboratory, in the end reaching the goal.

Lastly, we need to explain the three types of boot tested in this section. The iMI chosen for these tests was the same as mentioned above, a Linux iMI with the Ubuntu 16.04 LTS distribution.

Linux Server VDI In this case, the computation is done on one of the cluster nodes in a diskless VM, simulating a traditional VDI environment, with the particularity of using the iCBD platform's network boot. This variant was born due to its versatility during the development of the platform, since we can connect this VM to any of the networks (internal or labs) and perform tests on its operation.

Linux iCBD Native When we talk about this variant, we are addressing the boot of an iMI in a physical workstation in which, in this case, the OS Linux runs natively on top of the hardware, with no kind of resource to virtualisation.

Linux iCBD VM This last variant presents an interesting feature since it makes use of two iMIs. In a first phase, it boots as described in the previous point, but with two differences. The booted iMI is of an openSUSE 42.2², and this iMI has installed the VMware Workstation Player serving as a foundation to the next one. When the openSUSE iMI boot process ends, the iMI Ubuntu 16.04 is loaded by VMware Player and is then run on a virtual machine. All this without the user realising that he is using a virtual machine running on a different OS.

It is important to note that not only tests were performed with Linux iMIs, during the development of iMIs were tested with Windows 7 and Windows 10. It was decided not to include any of the tests performed with these iMIs because there was detected an unresolved issue that led the boot process to be abnormally slow. Something that was only found on the FCT NOVA site, since on the SolidNetworks site we did not detect any problems, and the Windows iMIs boot process is nominal.

iMI		iCBD-imgs	iCBD-Cache02
<i>Linux Server VDI</i>	iSCSI	453.5 MB	454.3 MB
	NFS	703.0 MB	702.1 MB
<i>Linux Client Native</i>	iSCSI	456.3 MB	453.6 MB
	NFS	704.2 MB	703.8 MB
<i>Linux Client VM</i>	iSCSI	834.1 MB	836.8 MB
	NFS	950.5 MB	952.8 MB

Table 5.5: Total data received after booting, given each boot variant and for both iMI providers

Benchmark Sequential Boot In this case, we perform the boot tests of the workstations in varying two parameters - link speed (1 Gbps and 100 Mbps) and protocol used (iSCSI and NFS). It has been found that by changing the protocol by which workstations boot, the amount of data that is transferred from the repository (iCBD-imgs or iCBD-cache02) is influenced as shown in the Table 5.5. We can attribute this variation to the fact that

²In this case, any other iMI could be used as a base (including natively run and then virtualised the same iMI), the version 42.2 of openSUSE was chosen because it was the iMI that exhibited the best stability in virtualising any other iMI, throughout the development process.

the NFS protocol is a bit more resource hungry, resulting in the need to transfer a larger amount of data. This ultimately means that the workstations that boot using this protocol will also spend more time in this process. As can be observed when comparing Figures 5.2 and 5.3.

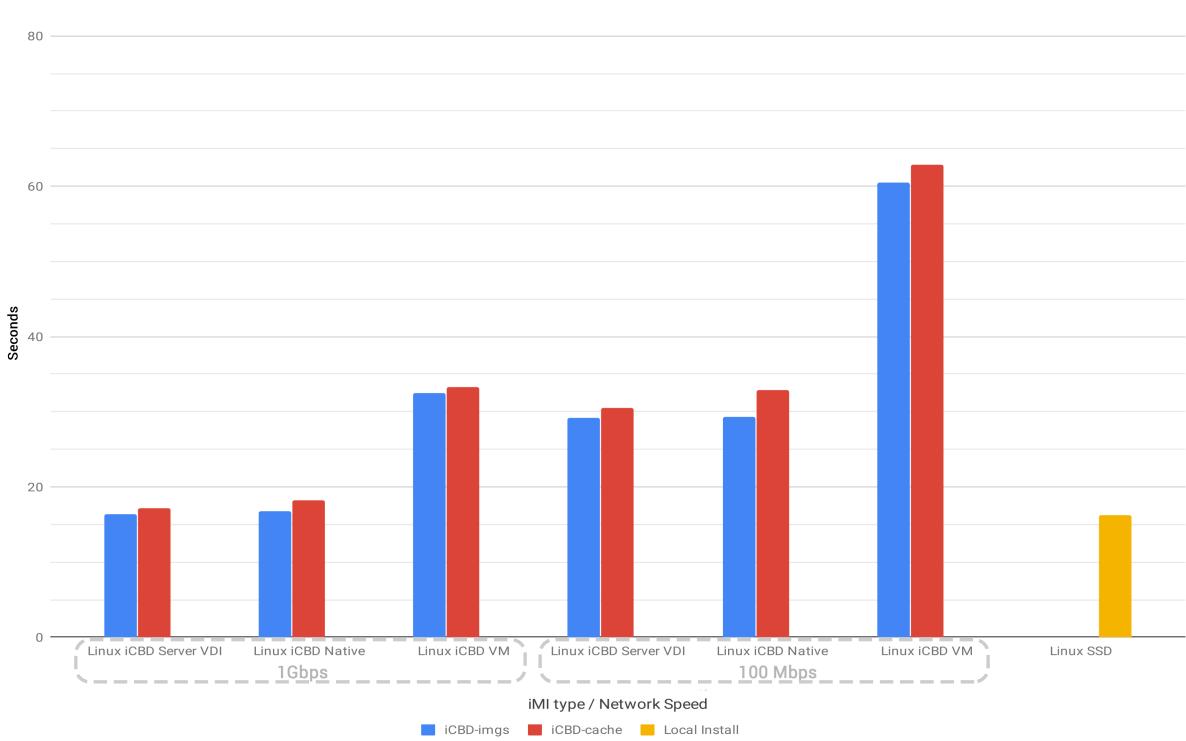


Figure 5.2: Mean Boot Time of five workstations using iSCSI (Sequential Boot Scenario), comparing iMI provider and network speed

As for running tests varying the speed of the links, a significant degradation can be observed, with the workstations taking much longer in the boot process when the link speed was set at 100 Mbps. Having the extreme case, when doing tests with the boot type Linux iCBD VM in which the average of the times passes the minute mark. Finally, we can observe that workstations booting from the iCBD-cache02 spend more time in this process than the ones that boot from iCBD-imgs, although latency in the first case is theoretically lower. We can attribute these results to the fact that iCBD-cache02 has much lower specifications than iCBD-imgs. Which leads us to believe that the solution can be vertically scalable. Metrics regarding the behaviour of both servers during one of these tests can be observed in the Figures 5.4 and 5.5.

Benchmark in a Boot Storm condition Finally we present the results of a test carried out in a boot storm scenario. Some simplifications have been made for this. First, no tests were performed using the Linux Server VDI boot type, so all values result from the measurement of boot time of the 15 workstations of both laboratories.

5.4. CACHE SERVER PERFORMANCE BENCHMARK

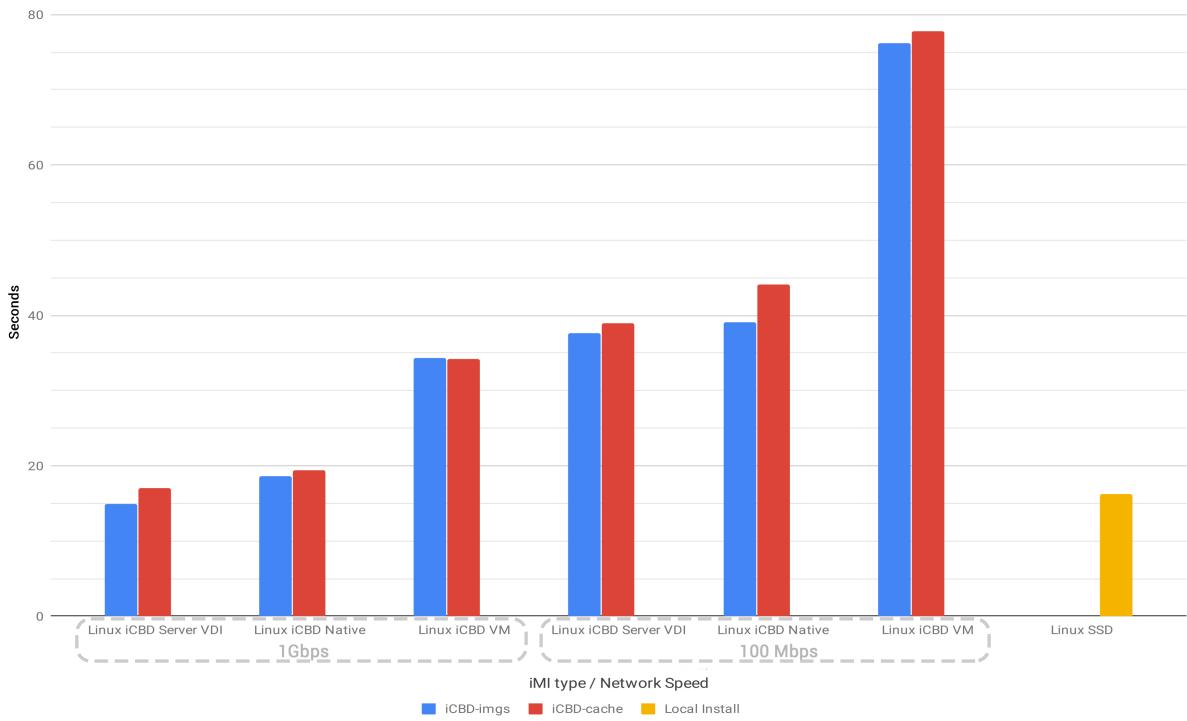


Figure 5.3: Mean Boot Time of five workstations using NFS (Sequential Boot Scenario), comparing iMI provider and network speed

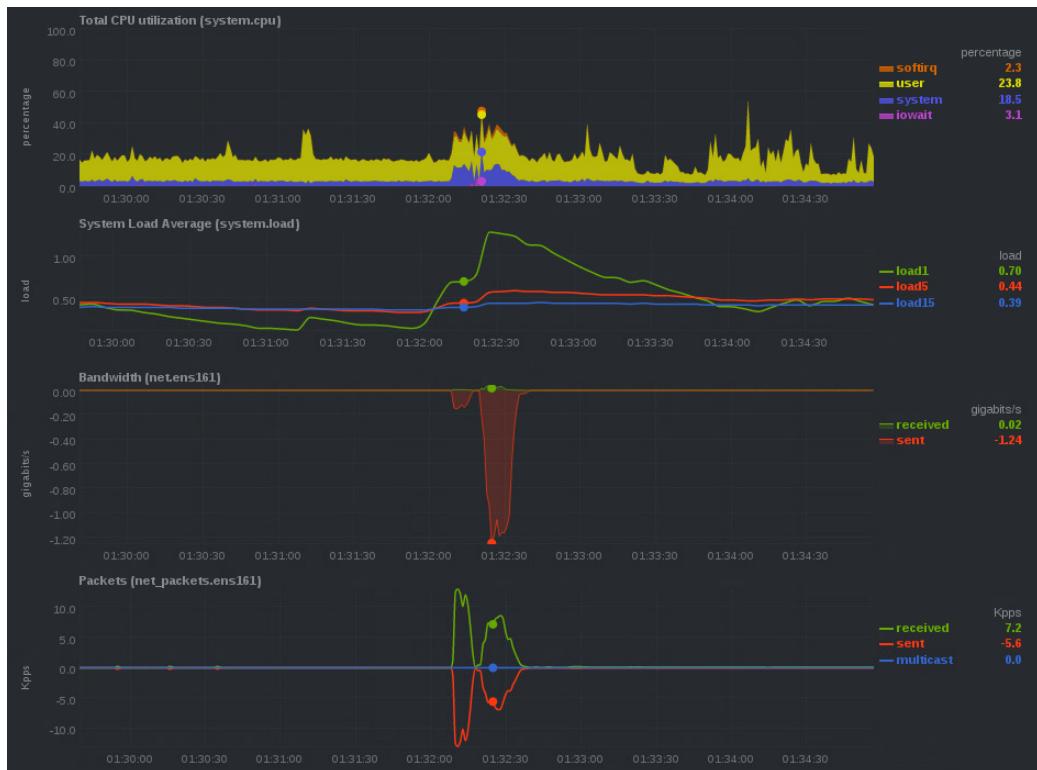


Figure 5.4: System metrics for iCBD-imgs on one run of the five workstations sequential boot scenario test



Figure 5.5: System metrics for iCBD-Cache02 on one run of the five workstations sequential boot scenario test

On the other hand, these tests were also performed only with the link speed of 1 Gbps³, utterly because the logistics related to the setup of this test are tremendous.

iMI		iCBD-imgs	iCBD-Cache02
<i>Linux iCBD Client Native</i>	iSCSI	20.035 s	23.020 s
	NFS	23.248 s	28.156 s
<i>Linux iCBD Client VM</i>	iSCSI	42.627 s	52.952 s
	NFS	44.734 s	54.840 s

Table 5.6: Comparison of boot times in a boot storm situation in both providers (iCBD-imgs and iCBD-cache02)

The last change we made in this test, was the fact that unlike in all other measurements presented in this chapter, we only measured one boot time per iMI (Linux iCBD Client Native and Linux iCBD Client VM) and per protocol (iSCSI and NFS) was performed, we present those results in Table 5.6.

Given the conditions described, we can still see encouraging results. In Figure 5.7, we show all the boot times of all 15 workstations when using the iSCSI protocol, achieving little variation in the times measured between all the machines and that the whole computing load of booting 15 workstations simultaneously does not substantially affect the

³Although we believe that we would obtain interesting results with tests at 100 Mbps, such as the fact that at this speed the boot times would skyrocket to values where a good user experience would be impractical.

5.4. CACHE SERVER PERFORMANCE BENCHMARK

machine that serves the iMIs to those workstations, as shown in the Figure 5.6.



Figure 5.6: System metrics for one run on the iCBD-Cache02 in a boot storm scenario

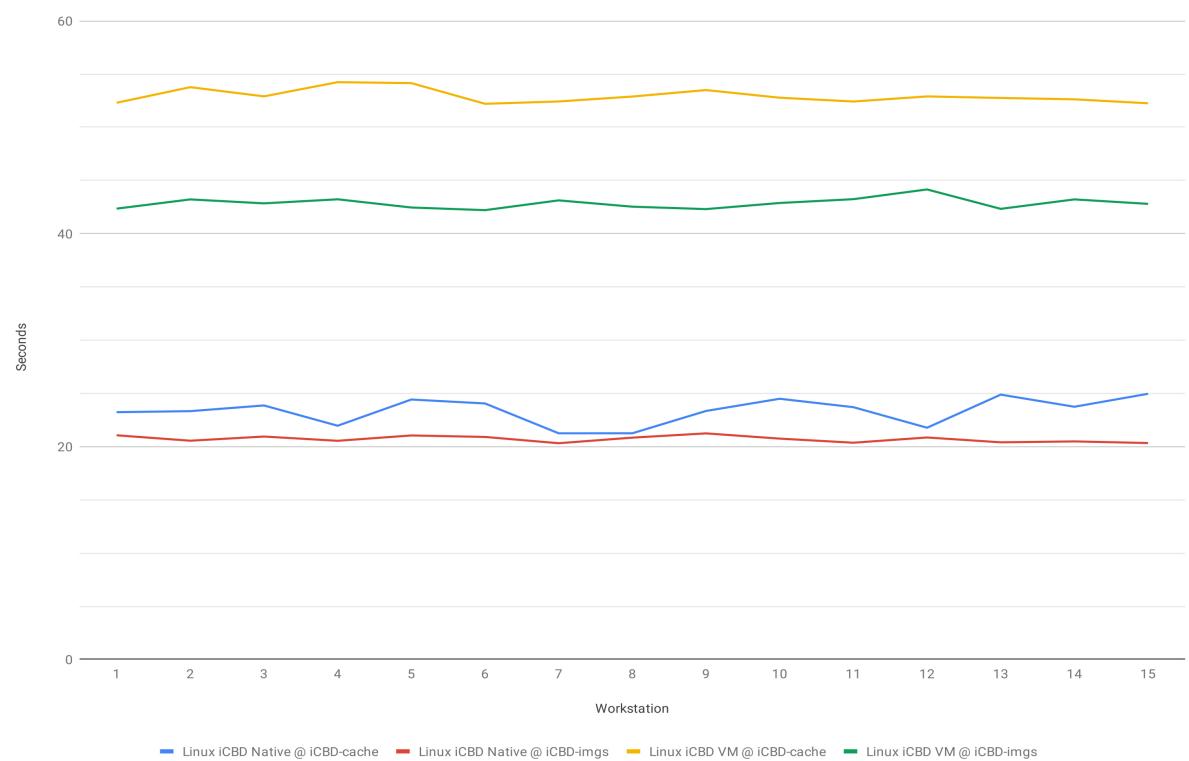


Figure 5.7: Boot Time of fifteen workstations simultaneously (Boot Storm Scenario) comparing iMI provider using iSCSI



CONCLUSIONS & FUTURE WORK

6.1 Conclusions

In this dissertation, we have architected, designed, implemented and benchmarked a distribute Replica and Cache System (RCS) to be integrated in the iCBD platform, which, in our perspective, satisfies all the goals we set out to achieve.

Our implementation was conducted with Btrfs in mind, but our modular design follows the well-known publish-subscribe model that, we believe, allows for an easy extension to other suitable storage platforms, even those which are based on a distinct paradigm, e.g., object-based storage.

We have shown that our implementation of a replication system for iMIs based on a Master - Replica model provides an efficient process for sending iMIs to their target locations in a geographically dispersed, multi-server environment, and guarantees some degree of fault-tolerance to the users of the iCBD platform. As for the RCS' control layer, it simplifies the entire process maintaining the state of the nodes.

We have documented the complete installation process of the iCBD platform, right from the start, in the DI-FCT NOVA site, and we overcome the challenges we faced; most of these challenges can also be found in a typical SME, so we believe that the information in the manual is applicable to other environments, outside academia. All this work culminated in an “Installation Manual” and has demonstrated the feasibility of integrating a Cache Server into the iCBD platform.

Finally, we evaluated both the Replication and the Cache components through a comprehensive functional validation, and we designed a benchmark to assess the performance of both the replication and the caching systems. In our opinion, the results clearly demonstrate the benefits of the proposed solutions.

In the replication system, we saw that the solution presented satisfies the requirements

and has a level of performance that is in line with what was expected.

In the case of the physical Cache Server, results consistently show a considerable increase in the boot time when compared to booting from a virtual one (VM) which was granted with far more resources. In our opinion, this is an excellent result, as it shows that if Cache Server nodes are vertically scalable (i.e., more resources translate to higher performance levels) and, as the service is already horizontally scalable by design, we have a solution that is scalable in all dimensions. Obviously, the poor result of the physical Cache Server used in the benchmark is a consequence of: a) utilising a PC and not a server and, b) on top of that the amount of RAM and number of CPUs was below par.

In the end, all our work validates the main ideas behind iCBD: it is, by design, an horizontally scalable architecture that, from the point of view of capital costs, may be well at the reach of Small and Midsize Businesses (SMBs).

6.2 Future Work

After spending many months working with iCBD, and not only for the immediate end of getting our masters degree, several ideas for future development have been popping up along the way.

The first one is to replace the Master-Server model used in the replication system by a peer-to-peer model, where replica nodes can “talk to each other”, allowing the transfer of iMI versions directly between replicas. This scenario would be especially advantageous in a circumstance where a Master Node was located in a geographic area far away from the Replicas, or even hosted in a public cloud. With several Replica Nodes installed on the same network, only one of the Replica nodes needed to receive the new version of the iMI; then that same node would send it directly to the other Replicas, possibly in a multicast or broadcast mode.

Another idea that was partially adopted in some services in the current implementation is the segmentation of iCBD’s multiple components into microservices, where each microservice is able to operate autonomously and coordinate itself with others using message exchange or any other interprocess communication mechanism. With this change, we believe that it would be possible to make better use of the platform resources and, even more relevant, microservices – implemented, e.g., as containers - do benefit from platform support for launching services independently of their location, as well as simplifying the development and deployment of new or updated platform services in parallel, without affecting the platform as a whole – e.g., these new versions can be deployed “live”. These approaches are usually referred to as DevOps.

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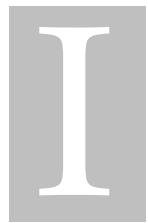
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A N N E X



I CBD-REPLICATION DOCUMENTATION

iCBD-Replication Documentation

Release 1.0.0

Luis Silva

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ICBD REPLICATION MODULE

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This site covers iCBD-Replication usage & API documentation. For basic info on what iCBD-rep is, including its public changelog & how the project is maintained, please see the git repo.

CHAPTER
ONE

API DOCUMENTATION

We maintain a set of API documentation, autogenerated from the python source code's docstrings (which are typically very thorough.) and for the RESTfull API (TODO: FUTURE)

1.1 icbdrep.ImageRepo module

```
class icbdrep.ImageRepo.ImageRepo(config)
Bases: object

addImage(image_name: str)
    Add an image name to the repository And checks if in that directory are already present some snapshots
    Args: image_name: name of the image to be added
    Returns: None
    Raises: DirNotFoundException, BTRFSPathNotFoundException, ImageAlreadyExistsException

addSnapshot(image_name: str, snap_number: str) → None
    Add a snapshot to a image
    Args: image_name: the name of the image to receive a snapshot snap_number: the snapshot
    Returns: None
    Raises: BTRFSSubvolumeNotFoundException, SnapshotAlreadyExistsException

deleteImage(image_name: str) → None
    Deletes a given image from the repository
    Args: image_name: the name of the image to be deleted
    Returns: None
    Raises: ImageNotFoundException

deleteSnapshot(image_name: str, snap_number: str) → lib.icbdSnapshot.icbdSnapshot
    Deletes a given snapshot of an image
    Args: image_name: the image to which the snapshot refers to snap_number: the snapshot number
    Returns: None
    Raises: SnapshotNotFoundException

getImageList() → typing.List[str]
    Get the list of the VM images present in the repo
    Returns: a list of strings with the images names
```

getImagepath (*image_name: str*) → str
Returns the path to the given image.

Args: *image_name*: the name of the image

Returns: a string with the path to the image

Raises: ImageNotFoundException

getLastSnapshot (*image_name: str*) → lib.icbdSnapshot.icbdSnapshot
Get the last snapshot from the given image.

Args: *image_name*: name of the image

Returns: an obj icbdSnapshot

Raises: ImageNotFoundException

getSnapshot (*image_name: str, snap_number: str*) → lib.icbdSnapshot.icbdSnapshot
Gets a specific snapshot given its number and the image name

Args: *image_name*: the name of the image *snap_number*: the number of the snapshot

Returns: an icbdSnapshot object

Raises: SnapshotNotFoundException

getSnapshotlist (*image_name: str*) → typing.List[lib.icbdSnapshot.icbdSnapshot]
Get the list of snapshots present in the repo for the given image. If there are no snapshots it returns a empty list.

Args: *image_name*: The image name that contains the snapshots

Returns: a list with the snapshots present in the repo

Raises: ImageNotFoundException

hasImage (*image_name: str*) → bool
Check if a given image name is present in the repository

Args: *image_name*: the image name to be checked

Returns: True if present, otherwise False

hasSnapshot (*image_name: str, snap_number: str*) → bool
Check if a snapshot is present in the given image

Args: *image_name*: the name of the image that should contain the snapshot *snap_number*: the snapshot

Returns: True if the snapshot is present, otherwise False

1.2 icbdrep.KeepAlive module

```
class icbdrep.KeepAlive.KeepAlive(interval=10, tries_num=3)
Bases: threading.Thread

keepAlive(pyro_bind: bool) → None
    Check a replica state and updates NS if needed.

    Args: pyro_bind: boolean True to use of the _pyroBind or False to use the ping method

    Returns: None
```

run ()

The main method of the class. This is triggered in the thread.start() call

Returns: None

stopKeepAlive () → None

Stop the execution of the keep alive thread. This should be part of the shutdown process.

Returns: None

1.3 icbdrep.MasterNode module

class icbdrep.MasterNode.MasterNode (node_config, ns_config, interactive_mode_flag: bool)

Bases: threading.Thread

addImage (image_name: str, node: int) → None

Add an image to the node repository

Args: image_name: the name of the image to be added node: the node where the image will be added

Returns: Node

delete_snapshot (image_name: str, snap_number: str, node: int) → None

Deletes a snapshot from a given image in a node.

Args: image_name: the image name snap_number: the snapshot number node: the node to do the deletion

Returns: None

exeCommand (line: str) → None

Receives a command line and interprets the content. Separating the various fields of the string into arguments, and calls the appropriated function.

Args: line: a line with the command to execute

Returns: None

getReplicasFromNS () -> (<class 'int'>, typing.Dict[int, Pyro4.core.Proxy])

Get a list of the replicas present in the system (Name Server) and saves them to the replicas proxy list

Returns: the number of found replicas

interactiveMode () → None

When in interactive mode, the server runs with a prompt, so that individual commands can be typed in

Returns: None

listImages (node: int) → None

List the collection of images available in a node.

Args: node: The node to list. (Master or one of the Replicas)

Returns: None

listReplicas () → None

List the replicas present in the system and prints to the console.

Returns: None

listSnapshots (node: int, image_name: str) → None

List the colection of snapshots of a given image in a node.

Args: node: The node to list (Master or one of the replicas) image_name: The image the snapshots refer to

Returns: None

registerInNS () → Pyro4.core.Daemon
Register the server in the Name Server

Returns: the registered daemon

run ()
The main method of the class. This is triggered in the thread.start() call

Returns: None

send (node: int, image_name: str, snapshot_number: str, blocking: bool, ssh: bool = False, compression: str = None) → None
Send Command - Instructs the replica to listen for a transfer, and sends the snapshot in the btrfs path
Args: node: the number of the node image_name: the name of the image snapshot_number: the number of the image blocking: if the function should block

Returns: None

stopMaster () → None
WARNING!! Don't use this! Only for testing and should be deprecated!

Returns: None

1.4 icbdrep.NameServer module

class icbdrep.NameServer.**NameServer** (config)
Bases: threading.Thread

run ()
The main method of the class. This is triggered in the thread.start() call

Returns: None

stopNS () → None
This function closes both the broadcast and name servers. This is called in the shutdown procedure.
Returns: None

1.5 icbdrep.ReplicaNode module

class icbdrep.ReplicaNode.**ReplicaNode** (rep_id: int, node_config, ns_config)
Bases: object

addImage (image_name: str) → bool
Add an image to the node's repository
Args: image_name: the name of the image to be added.

Returns: a boolean with the sucess of the operation

deleteSnapshot (image_name: str, snap_number: str) → lib.icbdSnapshot.icbdSnapshot
Delete a snapshot from the repo and FS
Args: image_name: the name of the image snap_number: the number of the snapshot
Returns: the snapshot which was deleted

getImagesList () → typing.List[str]

Get the list of images present in the replica

Returns: a list of strings

getLastSnapshot (image_name: str) → lib.icbdSnapshot.icbdSnapshot

Return the last snapshot of the given image.

Args: image_name: the name of the image

Returns: an obj icbdSnapshot

getName () → str

Get the replica name

Returns: a string with the name

getReplicaBtrfsAddress () → typing.Tuple[str, int]

Return the IP and PORT address for the btrfs transfer.

Returns: A tuple with an IP and PORT

getReplicaID () → int

Get the replica ID number. This should be a integer that originates from the

Returns: the replica ID

getSnapshotList (image_name: str) → typing.List[lib.icbdSnapshot.icbdSnapshot]

Return the list of snapshots stored in the repo for the given image name. Case there are no snapshots the list returned is empty. Case the image in args isn't in the repo return None.

Args: image_name: Image name to get the snapshot list.

Returns: a list with the snapshots.

ping () → str

Responds to a ping request with “pong”

Returns: “pong”

poisonPill () → None

Shutdown message to the replica

Returns: None

prepareReceive (image_name: str, snap_number: str) → bool

This function should precede the receive() call. Checks if the node wants the image in question or if the snapshot is already present.

Args: image_name: the name of the image snap_number: the name of the snap

Returns: a bool that indicates if the replica will accept the receive

receive (image_name: str, snap_number: str, compression: str = None)

Receives a snapshot

Returns: None

1.6 icbdrep.icbdrepd module

1.7 lib.benchmarkinglib module

```
class lib.benchmarkinglib.Benchmark(name)
Bases: object

    addRun(run: lib.benchmarkinglib.Run)

    get_name()

    mean()

    median()

    stdev()

class lib.benchmarkinglib.Run(interfaceName, runNumber=-1, imageName='default')
Bases: object

    getBtrfsTransferBytes()
        Returns:

    getBtrfsTransferPackets()
        Returns:

    getBtrfsTransferRuntime()
        Returns:

    getGlobalTransferRuntime()
        Returns:

    getIcbdBootTransferBytes()
        Returns:

    getIcbdBootTransferPackets()
        Returns:

    getIcbdBootTransferRuntime()
        Returns:

    getIscsiTargetTransferBytes()
        Returns:

    getIscsiTargetTransferPackets()
        Returns:

    getIscsiTargetTransferRuntime()
        Returns:

    startTimmer(transferType)
        Start a timmer for one of the transfer counters.

        Args: transferType: the type of the transfer to start counting time
        Returns: call the appropriated function

    stopTimmer(transferType)
        Stop a timmer for one of the transfer counters.

        Args: transferType: the type of the transfer to start counting time
        Returns: call the appropriated function
```

```
class lib.benchmarkinglib.linuxNetworkTraffic
```

Bases: object

```
static getInterfaceStats(interfaceName)
```

Args: interfaceName:

Returns:

1.8 lib.btrfslib module

```
class lib.btrfslib.BtrfsFsCheck
```

Bases: object

```
static isBtrfsPath(path: str)
```

Check if a given path is in fact present in a BTRFS tree

!!Caution!! : This function does not takes into account the fact that the path might not be a valid one.

Args: path: the path to be checked

Returns: true if present, otherwise falses

```
static isBtrfsSubvolume(path: str)
```

Check if the given path is a BTRFS subvolume / snapshot.

Args: path: the path to be checked

Returns: True if a subvolume, otherwise false

```
static searchForSnapshots(path: str) → typing.List[str]
```

Search the directory , and gets the snapshots that are already present

Args: path: the directory to be searched

Returns: a List with the name of the snapshot

```
class lib.btrfslib.BtrfsTool
```

Bases: object

```
static delete(path: str) → None
```

Wrapper for the BTRFS Tools subvolume delete command.

The method receives a path and calls the btrfs subvolume delete for that path.

Args: path: the path to the subvolume to delete

Returns: None

```
static receive(dst_path: str, src_port: int, compression: str = None)
```

Wrapper for the BTRFS Tools receive() command.

This method opens a socket and listens for a connection Then receives a snapshot and redirect it to the stdin of the BTRFS receive

Args: dst_path: the path of the image to place the snapshot src_port: the port to listening for the transfer

Returns: None

```
static send(src_path: str, dst_ip: str, dst_port: int, parent: str = None, compression: str = None)
```

Wrapper for the BTRFS Tools send() command.

This method is BLOCKING, it will wait for the conclusion of the send command. It uses regular sockets to send to an endpoint the data from the snapshot.

Args: src_path: the path of the snapshot to be send dst_ip: the IP of the destiny socket dst_port: the Port the destiny is listening

Returns: None

```
static sendNonBlock(src_path: str, dst_ip: str, dst_port: int, parent: str = None, compression: str = None)
```

Wrapper for the BTRFS Tools send() command.

This method is NON BLOCKING, it will NOT wait for the conclusion of the send command. It uses regular sockets to send to an endpoint the data from the snapshot.

Args: src_path: the path of the snapshot to be send dst_ip: the IP of the destiny socket dst_port: the Port the destiny is listening

Returns: None

```
static sendSSH(src_path: str, dst_ip: str, dst_port: int, parent: str = None, compression: str = None)
```

Wrapper for the BTRFS Tools send() command.

This method is BLOCKING, it will wait for the conclusion of the send command. It uses regular sockets to send to an endpoint the data from the snapshot.

Args: src_path: the path of the snapshot to be send dst_ip: the IP of the destiny socket dst_port: the Port the destiny is listening

Returns: None

```
static setReadOnly(path: str, state: bool) → None
```

Wrapper for the BTRFS Tools property set read only command.

This method sets the the read only property for the given subvolume in the path.

Args: path: the path to the subvolume state: a boolean of the state of the read only

Returns: None

1.9 lib.compressionlib module

```
class lib.compressionlib.compressionLib
```

Bases: object

```
static checkCompression(compression: str) → bool
```

Check if the given compression algorithm is available to use in the lib.

Args: compression: A string with the algorithm to check

Returns: A bool representing the availability of the chosen algo.

```
class lib.compressionlib.g_snappy
```

Bases: object

```
static compressStream(in_stream, out_stream, blocksize=65536) → None
```

Uses the Google snappy compress function to compress a stream of bytes.

Takes an incoming file-like object and an outgoing file-like object, reads data from “in_stream”, compresses it, and writes it to “out_stream”. “in_stream” should support the read method, and “out_stream” should support the write method.

Args: in_stream: a stream of bytes out_stream: a compressed stream blocksize: [optional] the size used for the buffer in bytes

Returns: None

static compress_native(*in_stream, out_stream, blocksize=65536*) → None
Wrapper for the snappy native stream compression

Args: *in_stream*: a stream of bytes *out_stream*: a compressed stream *blocksize*: [optional] the size used for the buffer in bytes

Returns:

static decompressStream(*in_stream, out_stream, blocksize=65536*) → None
Uses the Google snappy decompress function to handle a compressed stream.

Takes an incoming file-like object and an outgoing file-like object, reads data from “*in_stream*”, decompresses it, and writes it to “*out_stream*”. “*in_stream*” should support the read method, and “*out_stream*” should support the write method.

Args: *in_stream*: a compressed stream *out_stream*: the original stream of bytes *blocksize*: [optional] the size used for the buffer in bytes

Returns:None

static decompress_native(*in_stream, out_stream, blocksize=65536*) → None
Wrapper for the snappy native stream decompression

Args: *in_stream*: a compressed stream *out_stream*: the original stream of bytes *blocksize*: [optional] the size used for the buffer in bytes

Returns:

class lib.compressionlib.lz4

Bases: *object*

static compressStream(*in_stream, out_stream*) → None
Uses the lz4 compress function to compress a stream of bytes

Takes an incoming file-like object and an outgoing file-like object, reads data from “*in_stream*”, compresses it, and writes it to “*out_stream*”. “*in_stream*” should support the read method, and “*out_stream*” should support the write method.

Args: *in_stream*: a bytes input stream to be compressed *out_stream*: the compressed stream

Returns: None

static decompressStream(*in_stream, out_stream*) → None
Uses the lz4 decompress function to decompress a stream of bytes

Takes an incoming file-like object and an outgoing file-like object, reads data from “*in_stream*”, decompresses it, and writes it to “*out_stream*”. “*in_stream*” should support the read method, and “*out_stream*” should support the write method.

Args: *in_stream*: a compressed stream *out_stream*: the original bytes

Returns: None

class lib.compressionlib.z_lib

Bases: *object*

static compress2(*in_stream, out_stream*)
!!IN TESTING!! !!DONT USE THIS!!

Args: *in_stream*: *out_stream*:

Returns:

static compressStream (*in_stream, out_stream, blocksize=32768*) → None

Uses the zlib compress function to compress a stream of bytes.

Takes an incoming file-like object and an outgoing file-like object, reads data from “*in_stream*”, compresses it, and writes it to “*out_stream*”. “*in_stream*” should support the read method, and “*out_stream*” should support the write method.

Args: *in_stream*: a stream of bytes *out_stream*: a compressed stream *blocksize*: [optional] the size used for the buffer in bytes

Returns: None

static decompress2 (*in_stream, out_stream*)

!!IN TESTING!! !!DONT USE THIS!!

Args: *in_stream*: *out_stream*:

Returns:

static decompressStream (*in_stream, out_stream, blocksize=32768*) → None

Uses the zlib decompress function to handle a compressed stream.

Takes an incoming file-like object and an outgoing file-like object, reads data from “*in_stream*”, decompresses it, and writes it to “*out_stream*”. “*in_stream*” should support the read method, and “*out_stream*” should support the write method.

Args: *in_stream*: a compressed stream *out_stream*: the original stream of bytes *blocksize*: [optional] the size used for the buffer in bytes

Returns: None

1.10 lib.icbdSnapshot module

class lib.icbdSnapshot.icbdSnapshot (*mount_point: str, image_name: str, snapshot_number: str, icbd_boot_package_path: str, iscsi_target_folder: str*)

Bases: *object*

getICBDBootPackagePath()

Get a string with the full path to the iCBD Boot Package of the Image.

Returns: a string with the path

getISCSITarget()

Get a string with the path to the ISCSI target for this snapshot.

Returns: a string with the path

getImagePath() → str

Get a string with the formatted path, but without the snapshot number. This should be used as a destiny path

Returns: a string with the path in the format {/mountpoint/imagename}

getMountpointPath() → str

Get a string with only the mount point of the snapshot

Returns: the mountpoint

getPath() → str

Get a string with the full path of the snapshot, including the mountpoint and image name. Format: {mountpoint/imagename/snapshotnumber}

Returns: a string with the path

1.11 lib.restapilib module

```
class lib.restapilib.RestAPI (port: int = 5009)
```

Bases: object

iCBD-Replication Rest API Class

This instantiate the micro-framework Flack to provide a simple HTTP API for interacting with the system.

Note that every communication with this API uses JSON files. Responses are in JSON and an example can be found in the documentation of each method.

```
api = <flask_restful.Api object>
```

```
app = <Flask 'lib.restapilib'>
```

```
deleteImageVersion (replica, imi, version)
```

Delete a version of an iMI in a Replica Json response example:

Endpoint path : <IP>:<Port>/api/replicas/<replica>/imis/<imi>/versions/<version>/delete/

Returns:

```
listImageVersionsByReplica (replica, imi)
```

List the version of an iMI that are present in a Replica Json response example:

Endpoint path : <IP>:<Port>/api/replicas/<replica>/imis/<imi>/versions

Returns:

```
listImagesByReplica (replica)
```

List all iMIS present in a replica. Json response example:

Endpoint path : <IP>:<Port>/api/replicas/<replica>/imis

Returns:

```
listReplicas ()
```

List all the replicas registered in the system. Json response example:

Endpoint path : <IP>:<Port>/api/replicas

Returns:

```
listSystemImages ()
```

List all the iMIs present in the Master Node This will list all iMIs available to be transferred to any replica.

Json response example:

Endpoint path : <IP>:<Port>/api/master/imis

Returns:

```
listSystemImagesVersions (imi)
```

List all the versions of an iMIs present in the Master Node

Json response example:

Endpoint path : <IP>:<Port>/api/master/imis/<imi>/versions

Returns:

root()

Default root route endpoint. Mainly for testing

Endpoint path : <IP>:<Port>/api

Returns: a simple test string

sendImageVersionToReplica()

List all the versions of an iMIs present in the Master Node

Json response example:

Endpoint path : <IP>:<Port>/api/master/send?imi={imi}&version={version}&replica={replica}

Returns:

subscribeImage (replica, imi)

Replica subscribe to a iMI Json response example:

Endpoint path : <IP>:<Port>/api/replicas/<replica>/imis/subscribe/<imi>

Returns:

unsubscribeImage (replica, imi)

Replica unsubscribe to a iMI Json response example:

Endpoint path : <IP>:<Port>/api/replicas/<replica>/imis/unsubscribe/<imi>

Returns:

1.12 lib.serializerslib module

```
class lib.serializerslib.icbdSnapshotSerializer
    Bases: object

    static icbdSnapshot_class_to_dict (obj: lib.icbdSnapshot.icbdSnapshot)
    static icbdSnapshot_dict_to_class (class_name, dict)
```

1.13 lib.sshlib module

```
class lib.sshlib.sshTunnel (host, local_port, remote_port)
    Bases: object

    createTunnel (host, local_port, remote_port)
```

1.14 lib.utillib module

```
class lib.utillib.icbdUtil
    Bases: object

    logHeading (string)
        Big header for logger -[ “string” ]_____
        Args: string: a string to be placed inside the big header
        Returns: the string encapsulated in the header
```

prettify (obj)

Return pretty representation of obj. Useful for debugging.

Args: obj: the object to prettify

Returns: a pretty representation of obj

1.15 exceptions.ImageRepoException module

exception exceptions.ImageRepoException.BTRFSPathNotFoundException (message)

Bases: Exception

Raise when a BTRFS Path is not in the File System

exception exceptions.ImageRepoException.BTRFSSubvolumeNotFoundException (message)

Bases: Exception

Raise when a BTRFS Subvolume is not in the File System

exception exceptions.ImageRepoException.DirNotFoundException (message)

Bases: Exception

Raise when a Directory is not in the File System

exception exceptions.ImageRepoException.ImageAlreadyExistsException (message)

Bases: Exception

Raise when a Images already is present in the repo

exception exceptions.ImageRepoException.ImageNotFoundException (message)

Bases: Exception

Raise when a Images is not found

exception exceptions.ImageRepoException.SnapshotAlreadyExistsException (message)

Bases: Exception

Raise when a Snapshot already is present in the repo

exception exceptions.ImageRepoException.SnapshotNotFoundException (message)

Bases: Exception

Raise when a Snapshot is not found

1.16 exceptions.ReplicasException module

exception exceptions.ReplicasException.ReplicaNotFoundException (message)

Bases: Exception

Raise when a replica is not found

1.17 tests.benchLibTests module

tests.benchLibTests.dummyFunc()

tests.benchLibTests.main()

tests.benchLibTests.startCompleteRun()

1.18 tests.pyroNSTests module

```
class tests.pyroNSTests.NamingThrasher(nsuri, number)
    Bases: threading.Thread

    list()
    listprefix()
    listregex()
    lookup()
    register()
    remove()
    run()

tests.pyroNSTests.main()
tests.pyroNSTests.randomname()
```

1.19 tests.utilTests module

```
class tests.utilTests.TestMount(methodName='runTest')
    Bases: unittest.case.TestCase

    Our basic test class

    isBTRFS(path, assertVal)
    isSubvolume(path, assertVal)
    test_isBtrfsSet()
    test_isSubvolumeSet()
```

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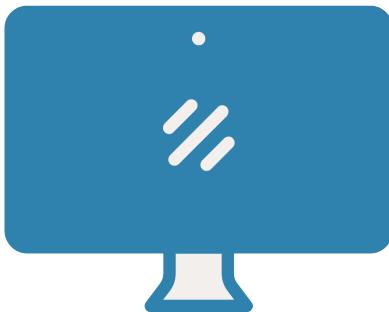
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A N N E X



iCBD INSTALLATION GUIDE



iCBD

iCBD Installation Protocol

Version 1.0.1 - Last Updated 9 Oct 2018

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In this document, we will detail all the steps needed to entirely install from scratch and start the iCBD Management Platform.

Pre-Requisites

What is needed:

- 3 x *CentOS 7 Minimum Install VM*
 - 2 Hard Drives (the extra for *BTRFS*)
 - 1 or more NICs (Depending on the VM)
- iCBD install files for each VM
- Some iCBD VM images

Attention - CentOS 7 Kernel Version! The Kernel `3.10.0-693.5.2.e17.x86_64` on CentOS 7 has manifested a problem with a core component of the *coreutils* tool command, the `cp` when used with option `--reflink=always`. To circumvent the issue is advised to use an older Kernel, such as `3.10.0-514.2.2.e17.x86_64` as we confirmed is working. This until Red Hat releases a new kernel with the bug fix.

Introduction

This tutorial assumes a fresh minimal install of a CentOS 7 Operating System. The installation procedure will cover all configurations needed for the implementation of VMs that will take a role in the platform. Some of the settings are specific for one of the roles, in this case, there will be a note in the step description.

iCBD Roles

The iCBD Management Platform consists of a minimum of three VM's, but for a more complex typology, we can mix in some cache servers and some clients. So we can have the following roles:

- *iCBD-imgs* - Primary repository of VM images and facilitator of the administration process
- *iCBD-rw* - Provides read/write space to the iCBD clients
- *iCBD-home* - Hosting of Home accounts to be used by iCBD clients
- *iCBD-cache* - Hosting of VM images closest to the clients
- *iCBD-Client* - A VM shell that don't have a hard disk and will boot from network

iCBD Networks

Also, there is the need to define multiple networks. Here, as we are using the VMware platform, there is the ability to design a Distributed VSwitch with various Port Groups, each one symbolising an individual network. The networks are:

On the iCBD-DSwitch (This distributed virtual switch only works inside the cluster)

- iCBD-Net
- iCBD-Adm-Net
- iCBD-Rep
- iCBD-CacheXX-Net

On the DI-DSwitch (Outside access to DI networks and Internet)

- DMZ-PRIV-DI
- DMZ-PUB-DI
- R-ENSINO-PRIV-DI

In the next table is showed the characteristics of each VM given its role. These properties mirror what is implemented in the Cluster at *DI - FCT NOVA*. Then we present two tables: one with the sizes used for the hard drives, and the other including the networks for the NICs of each VM.

VM Hardware by Role

	iCBD-imgs	iCBD-rw	iCBD-home	iCBD-CacheXX
CPUs (cores)	8	4	4	4
RAM (GB)	32	8	8	32
Hard Drives	2	2	2	2
NICs	3	1	1	2

Hard Drives by Role

	iCBD-imgs	iCBD-rw	iCBD-home	iCBD-CacheXX
Hard Drive 1 (Root FS)	16 GB	16 GB	16 GB	16 GB
Hard Drive 2 (BTRFS)	600 GB	300 GB	100 GB	600 GB

NICs by Role

	iCBD-imgs	iCBD-rw	iCBD-home	iCBD-CacheXX
NIC 1	DMZ-PRIV-DI (Internet)	iCBD-Net	iCBD-Net	iCBD-Net
NIC 2	iCBD-Net	X	X	iCBD-CacheXX-Net
NIC 3	iCBD-Adm-Net	X	X	X

First Step

Let's start:

The first thing we need is a vanilla VM with *CentOS 7* minimal install. This VM will be our basis. Many of the procedures that we will need to implement are more conveniently executed from a terminal in your machine, so probably is a good idea to configure an *SSH* access to the VM. Anyway, you will need to *SSH* to the VM in the future, so it's better to start this way.

Setup a static IP and configure SSH

Setup a static IP address.

Depending on the machine it may be that there is more than one network card installed. In the case of the `iCBD-imgs` this is true. So, I leave here the configuration prepared in this machine.

The VM `iCBD-imgs` has 3 NICs :

- NIC1
 - Port Group: DMZ-PRIV-DI
 - DVSwitch: DSwitch1 (DI-FCT Networks)
 - Used: Outside access
 - Config File - `vi /etc/sysconfig/network-scripts/INTERFACE_NAME`

```
HWADDR=00:50:56:96:A3:52 # Interface MAC Address
TYPE=Ethernet
BOOTPROTO=none
DEFROUTE=yes
IPV4_FAILURE_FATAL=no
IPV6INIT=no
IPV6_FAILURE_FATAL=no
```

```

NAME=ens192
ONBOOT=yes
IPADDR=10.170.137.98      # External IP
NETMASK=255.255.255.0
NM_CONTROLLED=no           # Doesn't let the Network Manager change the
config
PREFIX=24
GATEWAY=10.170.137.254    # Gateway for the .137 network
DNS1=10.130.10.25         # FCT DNS1
DNS2=10.130.10.26         # FCT DNS1
DOMAIN=ensino.priv.di.fct.unl.pt

```

- NIC2

- Port Group: iCBD-Net
- DVSwitch: iCBD-DSwitch
- Used: Main internal network. Platform clients connect were.
- Config File - `vi /etc/sysconfig/network-scripts/INTERFACE_NAME`

This NIC will be connected to a bridge, so this is the config for the interface, and then is shown the config for the bridge.

```

HWADDR=00:50:56:96:2E:9C
TYPE=Ethernet
#BOOTPROTO=none
#DEFROUTE=yes
#IPV4_FAILURE_FATAL=yes
#IPV6INIT=no
#IPV6_FAILURE_FATAL=no
NAME=ens224
ONBOOT=yes
#IPADDR=10.0.2.251
#PREFIX=24
BRIDGE=br0
#NETMASK=255.255.255.0
#NM_CONTROLLED=no
ZONE=internal

```

The Bridge config:

```

DEVICE=br0
STP=yes
TYPE=Brige
BOOTPROTO=none
DEFROUTE=yes
IPV4_FAILURE_FATAL=yes
IPV6INIT=no
NAME="Brige br0"
ONBOOT=yes
BRIDGIN_OPTS=priority=32768
IPADDR=10.0.2.251
PREFIX=24
ZONE=internal

```

- NIC3

- Port Group: iCBD-Adm-Net
- DVSwitch: Standard Switch
- Used: Internal network for the administration machines
- Config File - `vi /etc/sysconfig/network-scripts/INTERFACE_NAME`

```

HWADDR=00:50:56:96:74:85
TYPE=Ethernet
BOOTPROTO=none
DEFROUTE=yes
IPV4_FAILURE_FATAL=no
IPV6INIT=no
IPV6_FAILURE_FATAL=no
NAME=ens161
ONBOOT=yes
IPADDR=10.0.3.1
NETMASK=255.255.255.128
NM_CONTROLLED=no
PREFIX=24

```

SSH access without password

A configuration with password-less *SSH* access it's highly recommended since you will be connecting to the different servers a lot. A lot!

Still, the next step for your own machine is optional. But since in a later moment, it will be necessary to configure this between the servers and the physical machines the instructions are already here.

For some reference take a look at the next table. Each row represents a particular VM, and the columns indicate the VM keys that should be present in the `~/.ssh/authorized_keys`.

	iCBD-imgs	iCBD-rw	iCBD-home	iCBD-CacheXX	Your Machine
iCBD-imgs		✓	✓	✓	✓
iCBD-rw	✓		✓	✓	✓
iCBD-home	✓	✓		✓	✓
iCBD-CacheXX	✓	✓	✓	✓, other caches	✓

To generate an *RSA* key pair to work with version 2 of the *SSH* protocol, type the following command at a shell prompt: `ssh-keygen -t rsa`

Transfer your public key to `~/.ssh/authorized_keys`

Need the command ? `cat ~/.ssh/id_rsa.pub | ssh user@server "mkdir -p ~/.ssh && cat >> ~/.ssh/authorized_keys"`

Note: If you are cloning the main VM as a template for the other services, don't forget to create a new *RSA* key and add it to the remaining servers.

Install packages

Now we need to start building the environment with all the necessary tools to run iCBD.

So first run `yum update`, to make sure that all already installed packages are up to date.

Next we need to install all of these packages:

```
yum install net-tools
yum install hdparm
yum install Xorg
yum install gdm
yum install qemu-kvm
yum install virt-manager
yum install gcc
yum install kernel-headers
yum install kernel-devel
yum install epel-release
yum install htop
yum install httpd
yum install ntp
yum install firefox
yum install open-vm-tools
yum install open-vm-tools-desktop
yum install exportfs
yum install vnc
yum install xinetd
yum install tigervnc-server-applet
```

```
yum groupinstall fonts
yum groupinstall "X window system"

yum install kde-workspace
yum install ksysguard
yum install tftp
yum install tftp-server
yum install target-cli @@
yum install iscsi-initiator-utils
yum install scsi-target-utils
yum install firewall-config
yum install tcpdump
yum install libvirt
yum install qemu
yum install rsync
yum install php
yum install wget
yum install bind-utils
yum install spice-protocol
yum install spice-server
yum install iotop
yum install iftop
yum install libguestfs
yum install libguestfs-tools
yum install traceroute
yum install strace
yum install nmap
yum install whois
yum install ed
yum install sysstat
yum install rsh
yum install pure-ftpd
```

Setup a RSA key for the apache user

In the iCBD-imgs and iCBD-Cache roles the apache user will need to execute some ssh connections. For that the password-less login is paramount.

Since we generated a RSA pair for the root user we will use them also for the apache user.

Simply execute the following:

```
mkdir /usr/share/httpd/.ssh
cp /root/.ssh/id_rsa /usr/share/httpd/.ssh/
chown -R apache:apache /usr/share/httpd/.ssh/
chmod 0700 /usr/share/httpd/.ssh/
chmod 0600 /usr/share/httpd/.ssh/id_rsa
```

Setup a graphical environment

It's easier to perform much of the day to day operations if we have a graphical user interface. And given the today's available resources for a development environment, it helps. If you are setting up a production server, then it should be done with scripts..

To activate *KDE* just run `systemctl set-default graphical.target`

In the next restart, you will have a graphical interface instead of a console.

Update date & time

Make sure the time & date are updated

```
systemctl enable ntpd.service  
ntpd pool.ntp.org  
systemctl start ntpd.service
```

and to confirm running `date` and compare with our machine.

Disable SELinux

The Security-Enhanced Linux functionality enters into conflict with many components of the *iCBD* platform, this way there is the need for disabling it. `vi /etc/sysconfig/selinux`

Check if the flag is set to `SELINUX=enforcing`, if so change it either to `permissive` or `disabled` [1](#)

Ending Step One

Do a `reboot`, just to load everything up, including *KDE*.

Second Step

Now we start to lay the groundwork for the *iCBD* directories and much-needed mounts. In this sense, we need to start working with the *BTRFS* File System.

Format a second hard drive with BTRFS

You can check the available disks with `ls -l /dev | grep sd`

Let's assume that you have an empty disk ready to being formatted with *BTRFS* underneath

```
/dev/sdb
```

To format the disk with *BTRFS* do a `mkfs.btrfs /dev/sdb`

The above command makes use of the whole disk. But the `mkfs.btrfs` tool as multiple configurations and you can first create some partitions or even multiple disks in a *RAID* configuration and then format them in *BTRFS*. But for simplicity sake (and even taking into account some compartmentalisation issues) let's use the whole disk.

For some follow up on the matter of structuring the disks and multiple partitions there are numerous articles and tutorials on the web. [2](#)

Now you should see that there is a *BTRFS* file system in the OS.

Use `btrfs filesystem show` to make sure.

Third Step

Now the fun stuff. Mounts!

Caution: From this point on, it is necessary to pay close attention to the mounts, double checking them, as it is enough to fail one and the whole platform may not work.

Mounting the base for the iCBD BTRFS volume

The iCBD needs a "couple" of mount points, but every one of them will be under `/var/lib/`. Those will differ from server to server, given the task that it will perform. But this step is universal to every machine.

Let's create a temporary mount for the *BTRFS* disk we created earlier: Execute `mkdir /mnt/btrfs` and then `mount /dev/sdb /mnt/btrfs`.

As we are going to mount the root of the *BTRFS* file system under `/var/lib` there is the need to copy all files and directories first.

Create a sub-volume that will house the *lib* files `btrfs subv create /mnt/btrfs/Lib`, then copy everything to the new sub-volume `cp -a /var/lib/. /mnt/btrfs/Lib/`

Next mount the sub-volume `mount -o subvol=Lib /dev/sdb /var/lib` and check if the mount was sucessful `ls -lah /var/lib/`

Case it looks ok, edit the `fstab` file to make this change permanent: `vi /etc/fstab` Add the line `/dev/sdb /var/lib btrfs subvol=Lib 0 0`

(The arguments are separated by a tab and the numbers by a space

```
/dev/sdb[TAB]/var/lib[TAB]btrfs[TAB]subvol=Lib[TAB]0[SPACE]0 )
```

and `reboot`.

Fourth Step - iCBD-imgs

More sub-volumes!

These next steps are specific to the *iCBD-imgs VM*, that takes care of the administrations of the images, but also possesses the capability to serve them to the clients. In a future point, we will see the details for the other kind of roles.

Creating the iCBD sub-volumes

Let's create all the following sub-volumes:

```
btrfs subv create /var/lib/icbd
btrfs subv create /var/lib/icbd/.snap
btrfs subv create /var/lib/icbd/shared-vms
mkdir /var/lib/icbd/mounts
btrfs subv create /var/lib/icbd/mounts/vmware
btrfs subv create /var/lib/icbd/mounts/livirt
btrfs subv create /var/lib/icbd/mounts/tftpboot
btrfs subv create /var/lib/icbd/nfs_home
btrfs subv create /var/lib/icbd/nfs_root
btrfs subv create /var/lib/icbd/rw
btrfs subv create /var/lib/icbd/iso
btrfs subv create /var/lib/icbd/tmp
btrfs subv create /var/lib/icbd/icbd
```

The mounting of all this sub-volumes will come later.

Fifth Step - iCBD-imgs

In this installation package there should be a `iCBD-imgs_2017-11-17_bkk.tgz` file. This file is a backup of iCBD-Core and can be used to install.

Transfer the file to the VM, you can use a SSH feature for this:

```
scp iCBD-imgs_2017-11-17_bkk.tgz user@host:/var/lib/icbd
```

Navigate to `/var/lib/icbd/` on the VM and unzip the file directly to the folder `tar -xvf iCBD-imgs_2017-11-17_bkk.tgz`.

After this, you can clean up the folder by removing the file: `rm iCBD-imgs_2017-11-17_bkk.tgz`.

Attention - This backup does not contain the folder `/var/lib/icbd/mounts/tftpboot`

Now the remaining mounts I promised. Edit the `fstab` and add this lines:

```

/var/lib/icbd/mounts/vmware      /var/lib/vmware      none      rbind      0 0

/var/lib/icbd/mounts/etc/iscsi    /etc/iscsi      none      rbind      0 0
/var/lib/icbd/mounts/etc/tgt     /etc/tgt      none      rbind      0 0
/var/lib/icbd/mounts/etc/httpd   /etc/httpd      none      rbind      0 0
/var/lib/icbd/mounts/etc/xinetd.d /etc/xinetd.d  none      rbind      0 0
/var/lib/icbd/mounts/tftpboot    /var/lib/tftpboot  none      rbind
0 0

/var/lib/icbd/mounts/etc/hosts   /etc/hosts      none      bind      0 0
/var/lib/icbd/mounts/etc(exports /etc/exports   none      bind      0 0
/var/lib/icbd/mounts/etc/dnsmasq.conf /etc/dnsmasq.conf  none      bind
0 0

/var/lib/icbd/icbd      /var/lib/tftpboot/icbd      none      rbind      0 0

/var/lib/icbd/bin      /var/lib/icbd/exports/bin  none      rbind      0 0
/var/lib/icbd/include   /var/lib/icbd/exports/include none      rbind
0 0
/var/lib/icbd/client    /var/lib/icbd/exports/client  none      rbind      0
0

/var/lib/icbd/icbd      /var/lib/icbd/exports/icbd  none      rbind      0 0
/var/lib/icbd/tmp       /var/lib/icbd/exports/tmp   none      rbind      0 0
/var/lib/icbd/iso       /var/lib/icbd/exports/iso   none      rbind      0 0

/var/lib/icbd/shared-vms  /var/lib/icbd/exports/shared-vms  none
rbind      0 0
/var/lib/icbd/nfs_home   /var/lib/icbd/exports/nfs_home   none      rbind
0 0
/var/lib/icbd/nfs_root   /var/lib/icbd/exports/nfs_root   none      rbind
0 0
/var/lib/libvirt/images  /var/lib/icbd/exports/images   none      rbind
0 0

```

Save and [reboot](#)

Sixth Step - iCBD-imgs

Update the hosts file

Update `hosts` file. Remember, if any changes here done to this file before the last group of mounts this is now without effect. There is a sample `hosts` file in the install package. This server will serve as DHCP it's important that the IP's of the architecture are well defined.

Install the VMware Player.

Also, since we are working with virtualization, maby it's a good time to install one hypervisor.
Go to the VMware site and [download](#) VMware Workstation 12.

If there is the need for some help in the installation process, check this [link](#) to the VMware KB.

Add line to sysctl

`vi /etc/sysctl.conf` and add the line `net.ipv4.ip_forward=1`

Then exe the command `sysctl net.ipv4.ip_forward=1`

Activate NAT

Add direct rules to firewalld. Add the `--permanent` option to keep these rules across restarts.

```
firewall-cmd --direct --add-rule ipv4 nat POSTROUTING 0 -o eth_ext -j MASQUERADE
firewall-cmd --direct --add-rule ipv4 filter FORWARD 0 -i eth_int -o eth_ext -j ACCEPT
firewall-cmd --direct --add-rule ipv4 filter FORWARD 0 -i eth_ext -o eth_int -m state --state RELATED,ESTABLISHED -j ACCEPT
```

Source: <https://www.centos.org/forums/viewtopic.php?t=53819>

Firewall configuration

Open the firewall configuration GUI.

We need to configure the firewall to let a bunch of services let through. The profile we are going to use is the one named `internal`.

Then in this profile on the tab *Services* tick the following names:

```
dhcp
dhcpcv6-client
dns
ftp
http
https
iscsi-target
mdns
mountd
nfs
ntp
rpc-bind
rsyncd
samba
```

```
samba-client  
squid  
ssh  
tftp  
tftp-client
```

And in the *Masquerading* tab tick the showed box.

Lastly in the `options` dropdown select the option `Runtime to Permanent`, this way the changes are saved.

Sixth Step - iCBD-imgs

We are close to the end of the configurations on the *iCBD-imgs* server!

Launch the need services

There are some key services that need to be running in order to the platform work.

Make sure that these services are successfully running:

```
systemctl start vmware  
systemctl start vmware-workstation-server  
systemctl start libvиртd  
systemctl start dnsmasq  
systemctl start tftp * NO NEED  
systemctl start tgtd  
systemctl start nfs-server  
systemctl start httpd  
systemctl start ntpd
```

Check with `systemctl status -l [service_name]`

Don't forget to enable them for when a restart occur:

```
systemctl enable vmware-workstation-server  
systemctl enable libvиртd  
systemctl enable dnsmasq  
systemctl enable tftp  
systemctl enable tgtd  
systemctl enable nfs-server  
systemctl enable httpd  
systemctl enable ntpd
```

Other Roles Services

iCBD-rw

iCBD-rw sub volumes

```
btrfs subv create /var/lib/Home  
btrfs subv create /var/lib/icbd  
btrfs subv create /var/lib/icbd/.snap  
btrfs subv create /var/lib/icbd/nfs_home  
btrfs subv create /var/lib/icbd/nfs_root  
btrfs subv create /var/lib/icbd/nfs_rw  
btrfs subv create /var/lib/icbd/nfs_tmp  
btrfs subv create /var/lib/icbd/rw  
mkdir /var/lib/icbd-mounts  
btrfs subv create /var/lib/icbd-mounts/tftpboot
```

iCBD-rw Services

```
systemctl start tgtd  
systemctl start nfs-server
```

iCBD-rw fstab

```
/dev/sdb      /var/lib      btrfs    subvol=Lib      0 0  
/dev/sdb      /home       btrfs    subvol=Home     0 0  
  
/var/lib/icbd/nfs_home  /var/lib/icbd/exports/nfs_home  none    rbind   0 0  
/var/lib/icbd/nfs_root  /var/lib/icbd/exports/nfs_root   none    rbind   0 0  
/var/lib/icbd/rw       /var/lib/icbd/exports/rw        none    rbind   0 0  
/var/lib/icbd-mounts/etc/hosts  /etc/hosts      none    bind    0 0  
/var/lib/icbd-mounts/etc/exports  /etc/exports    none    bind    0 0  
/var/lib/icbd-mounts/tftpboot   /var/lib/tftpboot   none    rbind   0 0  
/var/lib/icbd-mounts/etc/tgt    /etc/tgt       none    rbind   0 0  
/var/lib/icbd-mounts/etc/httpd  /etc/httpd     none    rbind   0 0  
/var/lib/icbd-mounts/etc/tgt/macs.d  /var/lib/icbd/exports/macs.d  
none    rbind   0 0
```

iCBD-home

iCBD-home sub volumes

```
btrfs subv create /var/lib/icbd  
btrfs subv create /var/lib/icbd/.snap  
btrfs subv create /var/lib/icbd/nfs_home  
btrfs subv create /var/lib/icbd/nfs_root  
btrfs subv create /var/lib/icbd/exports/nfs_home  
btrfs subv create /var/lib/icbd/exports/nfs_root
```

iCBD-home fstab

```
/dev/sdb      /var/lib      btrfs    subvol=Lib      0 0
/var/lib/icbd/mounts/etc/exports   /etc/exports  none     bind      0 0
```

iCBD-home Services

```
systemctl start nfs-server
```

iCBD-Cache

In the file `/etc/hosts` there is the need to change one line. Where is

```
10.0.2.251 imgs.icbd.local boot.icbd.local root.icbd.local adm-s.icbd.local
```

now we should have two lines:

```
10.0.2.251 imgs.icbd.local
```

```
10.1.2.251 boot.icbd.local root.icbd.local adm-s.icbd.local
```

The second IP is the subnet to be used on the second NIC of the cache server, and only to communicate with clients.

iCBD-cache sub volumes

```
btrfs subv create /var/lib/icbd
btrfs subv create /var/lib/icbd/.snap
btrfs subv create /var/lib/icbd/shared-vms
mkdir /var/lib/icbd/mounts
btrfs subv create /var/lib/icbd/mounts/vmware
btrfs subv create /var/lib/icbd/mounts/livirt
btrfs subv create /var/lib/icbd/mounts/tftpboot
btrfs subv create /var/lib/icbd/nfs_home
btrfs subv create /var/lib/icbd/nfs_root
btrfs subv create /var/lib/icbd/rw
btrfs subv create /var/lib/icbd/iso
btrfs subv create /var/lib/icbd/tmp
btrfs subv create /var/lib/icbd/icbd
```

iCBD-cache fstab

```
/dev/sdb      /var/lib      btrfs    subvol=Lib      0 0
/var/lib/icbd/mounts/vmware      /var/lib/vmware  none     rbind      0 0
/var/lib/icbd/mounts/etc/iscsi  /etc/iscsi     none     rbind      0 0
```

```

/var/lib/icbd/mounts/etc/tgt           /etc/tgt      none    rbind   0 0
/var/lib/icbd/mounts/etc/httpd        /etc/httpd     none    rbind   0 0
/var/lib/icbd/mounts/etc/xinetd.d    /etc/xinetd.d  none    rbind   0 0
/var/lib/icbd/mounts/tftpboot       /var/lib/tftpboot none    none    0 0
rbind   0 0

/var/lib/icbd/mounts/etc/hosts      /etc/hosts     none    bind    0 0
/var/lib/icbd/mounts/etc(exports)  /etc(exports)  none    bind    0 0
/var/lib/icbd/mounts/etc/dnsmasq.conf /etc/dnsmasq.conf none    none    0 0
bind   0 0

/var/lib/icbd/icbd      /var/lib/tftpboot/icbd      none    rbind   0 0
/var/lib/icbd/bin      /var/lib/icbd(exports)/bin      none    rbind   0 0
/var/lib/icbd/include  /var/lib/icbd(exports)/include  none    rbind   0 0
/var/lib/icbd/client   /var/lib/icbd(exports)/client   none    rbind   0 0

/var/lib/icbd/icbd      /var/lib/icbd(exports)/icbd      none    rbind   0 0
/var/lib/icbd/tmp      /var/lib/icbd(exports)/tmp      none    rbind   0 0
/var/lib/icbd/iso      /var/lib/icbd(exports)/iso      none    rbind   0 0

/var/lib/icbd/shared-vms          /var/lib/icbd(exports)/shared-vms
none    rbind   0 0
/var/lib/icbd/nfs_home   /var/lib/icbd(exports)/nfs_home  none    rbind   0 0
/var/lib/icbd/nfs_root   /var/lib/icbd(exports)/nfs_root  none    rbind   0 0
/var/lib/libvirt/images /var/lib/icbd(exports)/images  none    rbind   0 0

home.icbd.local:/nfs_home      /var/lib/icbd/nfs_home  nfs4    _netdev,rw
0 0
home.icbd.local:/nfs_root      /var/lib/icbd/nfs_root  nfs4    _netdev,rw
0 0
data.icbd.local:/rw      /var/lib/icbd/rw      nfs4    _netdev,rw      0 0
data.icbd.local:/rw      /var/lib/icbd(exports)/rw      nfs4    _netdev,rw
0 0
data.icbd.local:/macs.d /etc/tgt/macs.d nfs4    _netdev,rw      0 0

```

iCBD-cache Services

```

systemctl start libvиртd
systemctl start dnsmasq
systemctl start tftp *NO NEED - USE DNSMASQ*
systemctl start tgtd
systemctl start nfs-server
systemctl start httpd
systemctl start ntpd

```

Change Log

2017-11-21 — Version 0.0.1 — Creation of this document.

2017-12-01 — Version 0.0.1 — Created the base structure for the description of the installation steps.

2017-12-10 — Version 0.0.1 — Added much of the content for the installation of the three main VMs. Some organisation is needed!

2017-12-12 — Version 0.0.1 — Step One formatted and updated.

2017-12-16 — Version 0.0.1 — Reference added.

2017-12-18 — Version 0.0.1 — Step Two edited.

2018-01-12 — Version 0.0.1 — Every step was edited

2018-01-14 — Version 1.0.0 — All steps tested in the installation of one physical cache server

2018-01-30 — Version 1.0.1 — Some clarifications on the introduction and on the cache server.

2018-08-15 — Version 1.0.1 — Removed email from Reditus

2018-10-09 — Version 1.0.1 — Added instructions on setting up RSA keys for the apache user.

References

[CentOS 7 Documentation - Enable or Disable SELinux](#)

[HowToForge - A Beginners Guide To btrfs](#)



BUG ON BTRFS AFFECTING COREUTILS TOOL

III.1 Bug Report

The bug was reported in both *CentOS Bug Tracker* and *Red Hat Bugzilla* on 4 of December of 2017.

Description of problem: In a CentOS 7 VM with kernel 3.10.0-693.5.2.el7.x86_64 including a mounted disk formatted with Btrfs and btrfs-progs v4.9.1. When executing a copy of files with the command "`cp --reflink=always`" the command fails with the indication "*failed to clone 'someFile': Operation not supported*"

Issue: The above-mentioned copy fails, but in the files are created with zero bytes in the destination folder. While trying to find the cause, it seems to be some bug in the ioctl operation. A strace log of the copy operation can be found in the uploaded files.

This problem only manifests itself in the kernel 3.10.0-693.5.2.el7.x86_64. If the same operation is executed in the system with the kernel 3.10.0-514.2.2.el7.x86_64 all goes well. More evidence that this is probably a bug introduced in this version of the kernel can be found in the git repository in the first commit of the new kernel¹. In the file "SPECS/kernel.spec" line 15011² that some changes were made in the ioctl - "[fs] btrfs: fix uninit variable in clone ioctl (Bill O'Donnell) [1298680]"

As a workaround, an older version of the kernel can be used, but this is not optimal, as future releases may have the same problem.

How reproducible: It is always reproducible. Happens every time.

¹<https://git.centos.org/commit/rpms!kernel.git/d6bfd60741b14479a15b43acaa1ea5a8d73df543>

²<https://git.centos.org/blob/rpms!kernel.git/d6bfd60741b14479a15b43acaa1ea5a8d73df543/SPECS!kernel.spec#L15011>

Steps to Reproduce:

1. In a Btrfs mount execute:
2. dd if=/dev/urandom of=testb bs=1024k seek=1024 count=128
3. cp --reflink=always testb testb_copy

Actual results: The copy operation returns with "failed to clone 'testb': Operation not supported" and creates a zero bytes file in the destination of the copy.

Expected results: A clone of the file, looking precisely the same as the original with the same size.

III.2 Resolution

On 5 of April of 2018, the problem was acknowledged by Red Hat, and a patch was provided. However, also informed that the fix would not be included in later RHEL7 releases, due to Red Hat deciding to deprecate Btrfs as of RHEL7.5.

```

execve("/usr/bin/cp", ["cp", "--reflink=always", "testb", "test_reflink"], /* 33 vars */) = 0
(...)

access("/etc/selinux/config", F_OK)      = 0
open("/usr/lib/locale/locale-archive", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=106070960, ...}) = 0
mmap(NULL, 106070960, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f43ee219000
close(3)                                = 0
open("/usr/share/locale/locale.alias", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=2502, ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f43f59db000
read(3, "# Locale name alias data base.\n#", ..., 4096) = 2502
read(3, "", 4096)                        = 0
close(3)                                = 0
munmap(0x7f43f59db000, 4096)           = 0
open("/usr/lib/locale=UTF-8/LC_CTYPE", O_RDONLY|O_CLOEXEC) = -1 ENOENT (No such file or directory)
geteuid()                                 = 0
stat("test_reflink", {st_mode=S_IFREG|0644, st_size=0, ...}) = 0
stat("testb", {st_mode=S_IFREG|0644, st_size=1207959552, ...}) = 0
stat("test_reflink", {st_mode=S_IFREG|0644, st_size=0, ...}) = 0
open("testb", O_RDONLY)                  = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=1207959552, ...}) = 0
open("test_reflink", O_WRONLY|O_TRUNC)    = 4
fstat(4, {st_mode=S_IFREG|0644, st_size=0, ...}) = 0
ioctl(4, BTRFS_IOC_CLONE or FICLONE, 3) = -1 EOPNOTSUPP (Operation not supported)
open("/usr/lib64/charset.alias", O_RDONLY|O_NOFOLLOW) = -1 ENOENT (No such file or directory)
write(2, "cp: ", 4)                      = 4
write(2, "failed to clone 'test_reflink' f"..., 43) = 43
write(2, ": Operation not supported", 25) = 25
write(2, "\n", 1)                         = 1
close(4)                                = 0
close(3)                                = 0
lseek(0, 0, SEEK_CUR)                   = -1 ESPIPE (Illegal seek)
close(0)                                = 0
close(1)                                = 0
close(2)                                = 0
exit_group(1)                           = ?
+++ exited with 1 +++

```

Listing 5: Strace of the cp --reflink=always command

```
--- a/fs/btrfs/super.c
+++ a/fs/btrfs/super.c
@@ -2191,7 +2191,7 @@ static struct file_system_type btrfs_fs_type = {
     .name          = "btrfs",
     .mount         = btrfs_mount,
     .kill_sb       = btrfs_kill_super,
-    .fs_flags      = FS_REQUIRES_DEV | FS_BINARY_MOUNTDATA,
+    .fs_flags      = FS_REQUIRES_DEV | FS_BINARY_MOUNTDATA | FS_HAS_FO_EXTEND,
 };
 MODULE_ALIAS_FS("btrfs");
```

Listing 6: Btrfs patch on a/fs/btrfs/super.c

A N N E X

IV

I CBD CLUSTER RACK DIAGRAM

ANNEX IV. ICBD CLUSTER RACK DIAGRAM

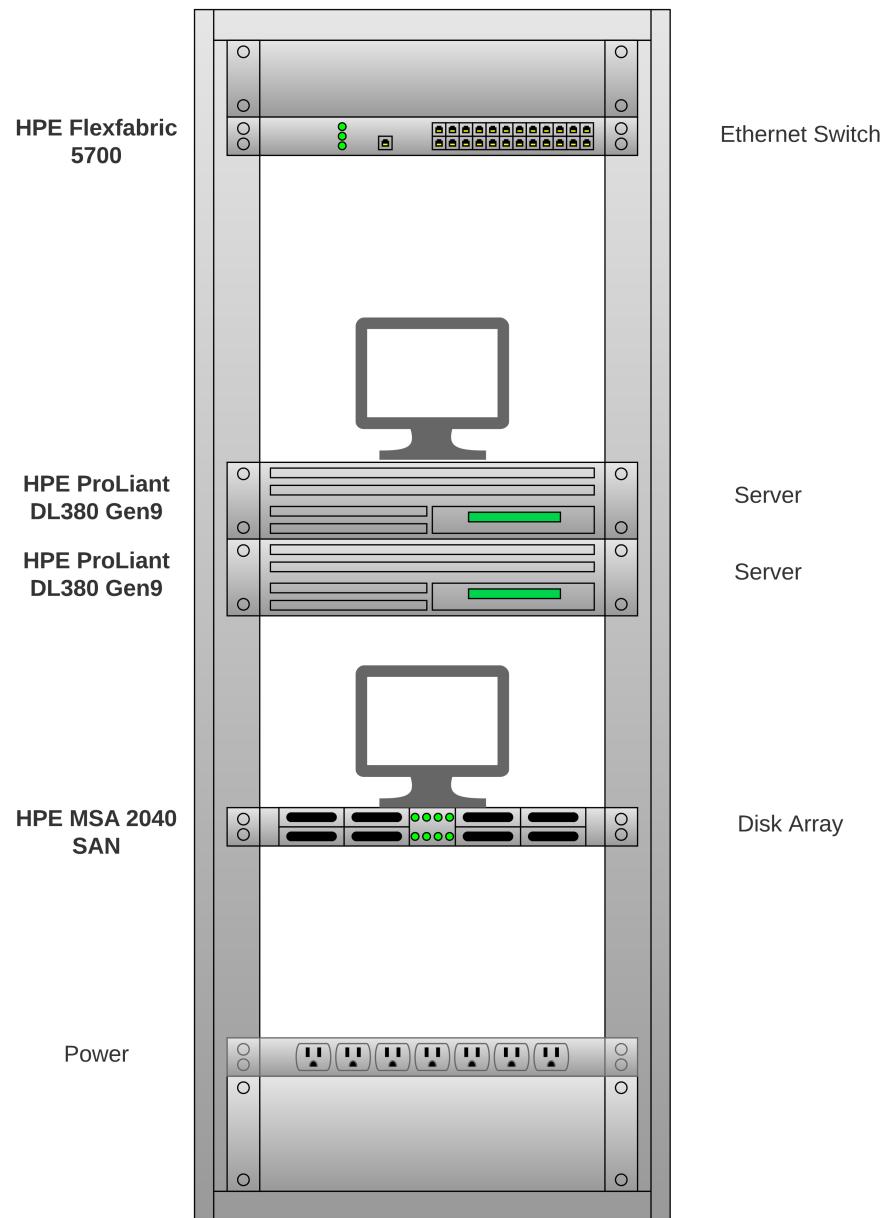


Figure IV.1: iCBD Cluster Rack Diagram