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Checkpointing as a Service in Heterogeneous Cloud Environments

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***Abstract*—A non-invasive, cloud-agnostic approach is demonstrated for extending existing cloud platforms to include checkpoint-restart capability. Most cloud platforms currently rely on each application to provide its own fault tolerance. A uniform mechanism within the cloud itself serves two purposes: (a) direct support for long-running jobs, which would otherwise require a custom fault-tolerant mechanism for each application; and (b) the administrative capability to manage an over-subscribed cloud by temporarily swapping out jobs when higher priority jobs arrive. An advantage of this uniform approach is that it also supports parallel and distributed computations, over both TCP and InfiniBand, thus allowing traditional HPC applications to take advantage of an existing cloud infrastructure. Additionally, an integrated health-monitoring mechanism detects when long-running jobs either fail or incur exceptionally low performance, perhaps due to resource starvation, and proactively suspends the job. The cloud-agnostic feature is demonstrated by applying the implementation to two very different cloud platforms: Snooze and OpenStack. The use of a cloud-agnostic architecture also enables, for the first time, migration of applications from one cloud platform to another.**

***Keywords*- checkpoint-restart, cloud computing, distributed application, infrastructure-as-a-service, virtualization, scalability, self-healing.**

I. INTRODUCTION

Cloud computing provides users with the illusion of an infinite pool of resources available over the Internet, from which they can access on demand and through self-service the resources they need for their applications. In less than a decade numerous cloud providers have flourished, each of them operating one or several data centers in different locations. Cloud providers target transparent failure and maintenance management, with the twin goals of satisfying their customers, and providing the high resource utilization that maximizes their profit. Many failure, reconfiguration and resource management strategies rely on the ability to migrate virtual machines (VMs) both between data centers and within a single data center. Customers want their applications to be executed reliably in the cloud, and they seek to escape the vendor lock-in phenomenon by taking advantage of a market of heterogeneous clouds.

We propose a novel *Checkpointing as a Service* approach, which enables application checkpointing and migration in heterogeneous cloud environments. Our approach is based on a non-invasive mechanism to add fault tolerance to an existing cloud platform *after the fact*, with little or no modification to the cloud platform itself. It achieves its cloud-agnostic property by using an external checkpointing package, independent of the target cloud platform.

Such a cloud-agnostic checkpointing service is important for at least three distinct reasons:

1) provision of fault tolerance for long-running tasks;
2) improved cloud efficiency (low-priority applications can be suspended to stable storage, and restored only when idle CPU cycles are available); and
3) migration of tasks between distinct IaaS clouds (e.g., between one operated by the Snooze system and one operated by the OpenStack system).

The proposed *Cloud-Agnostic Checkpointing Service* (CACS) is retro-fitted into multiple cloud platforms. This is demonstrated for two cloud platforms: Snooze and OpenStack.

A necessary component of CACS is a health-monitoring mechanism that not only detects when an application has "died", but generally when an application is unhealthy. Detecting the latter is non-trivial, since only the application developer knows if the termination or non-responsiveness of one process is fatal to the overall computation. Hence, a hook is provided for each application to determine its own "health".

Our contributions are three-fold:

- We provide the first transparent checkpointing scheme for centralized, parallel and distributed computations in the Cloud.
- The transparent checkpointing scheme is *cloud-agnostic*. The minimal assumptions of this approach allow it to be extended to most cloud architectures.
- Migration of computations among heterogeneous clouds is provided.

CACS employs the DMTCP package [1], a checkpointer for distributed multithreaded applications. This was chosen for its transparent support of distributed applications, including both TCP/IP and the InfiniBand network [2].

Moreover, we show that our approach toward checkpointing and migration scales with application size and with the number of applications hosted in a data center.

The remainder of this paper is organized as follows. Section II presents further background and motivation for the approach. In Section III we discuss the principles that guided the design of the cloud checkpointing service. Section IV

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provides an overview of CACS. Section V presents some typical scenarios, from application submission through checkpoint, recovery and/or migration to a new cloud, and finally application termination. Section VI presents our prototype implementation. In Section VII we analyze the results from a first experimental evaluation. Section VIII describes the related work, while the conclusions are presented in Section IX.

II. MOTIVATION

The cloud-agnostic checkpointing service is intended to provide a single checkpointing solution for heterogeneous computing services. This eliminates the need for each computing service to implement its own checkpointing solution. Such solutions are required not only for long-lived computations, but also for numerous other use cases.

A. Context: IaaS and Heterogeneity among Clouds

IaaS clouds provide resources on demand to their customers in the form of virtual machines. IaaS clouds are heterogeneous, each coming with its own marketplace of *Virtual Machine Images* (VMI). Customers of an IaaS cloud provider select VMIs among those offered. Different VMIs correspond to different, possibly customized, combinations of an operating system kernel, an OS distribution, and a processor architectures (32- or 64-bit). Instances are characterized by the amount and type of resources they use (e.g., number of cores, memory capacity, disk capacity).

The IaaS cloud management system manages the life cycle of a VM from submission to termination. In particular, it allocates the server resources among the VMs and performs VM scheduling. Servers and VMs are monitored in order to determine efficient resource management strategies. In a cloud environment, a distributed application is executed using a set of interconnected VMs called a *virtual cluster*.

Different cloud environments also introduce heterogeneity among dimensions other than those described in the previous paragraph. Servers may have different hardware configurations (e.g., Intel versus AMD processors), and may run different combinations of VMs and hypervisors (e.g., KVM/QEMU, Xen, and Linux containers).

A sufficiently robust checkpoint-restart package, such as the DMTCP package used here, can overcome these sources of heterogeneity. As a prerequisite, an end user must design her applications for a common denominator: compiling for the intersection of Intel and AMD instruction sets, avoiding the most recent system calls in order to provide backward compatibility, programming scalability to adjust for fewer or more cores, and even compiling for a 32-bit instruction set if a combination of 32- and 64-bit CPUs is anticipated. In this way, a cloud-agnostic checkpointing service can directly migrate applications among such heterogeneous resources.

Finally, a cloud-agnostic checkpointing service must be tolerant of the different types of IaaS cloud management systems that exist today. These include OpenStack [3] (widely adopted in production data centers), Nimbus [4] (targeting scientific computing), and Eucalyptus [5], OpenNebula [6] and Snooze [7] (originating from academia), and Amazon EC2 (the most widely used public commercial cloud). IaaS cloud systems may use different VM disk image formats (e.g. QCOW, VMDK) and provisioning methods. They may provide different APIs for storage and VM management. However, some popular interfaces (EC2 for VM management and S3 for storage, for example) have become de-facto standards. Recently, there have been a number of emerging standard APIs such as DMTF CIMI [8] and OGF OCCI [9], which have not yet become mainstream.

B. Use Cases

Many motivating use cases demonstrate the need for a portable efficient cloud checkpointing service. A first use case is fault-tolerant application execution in the cloud. Long-running jobs (such as OpenMP-based or MPI-based scientific applications) should be periodically checkpointed, so that they can be restored from their last checkpoint in the event of a failure.

Ideally, it should be possible to restore an application either in the same data center or in another one from the same cloud provider to survive catastrophic failures affecting a whole data center. However, although a second data center may be available, it may be running under a different type of infrastructure. This gives rise to the second use case: migration among heterogeneous clouds.

A third use case occurs when the cloud provider needs to transparently carry out maintenance operations. Providers can stop all applications and checkpoint them or migrate them to other clusters, before taking down a cluster for maintenance.

A fourth use case occurs in the scientific world, in the framework of advanced VM scheduling algorithms. Periods of low demand may lead to potentially low utilization rates. A VM scheduler attempts to increase resource utilization. Opportunistic preemptible leases running on backfill VMs have been proposed for this case by Marshall et al. [10]. Such leases give a user access to a resource at an indeterminate time and for an indeterminate amount of time, but are less expensive than traditional on-demand leases. Transparent cloud-agnostic checkpointing allows any scientific application to use such a lease.

Proactive cloud migration provides a fifth use case. For a cloud provider operating multiple possibly heterogeneous data centers it is desirable to be able to migrate VMs from one cloud to another. Energy-efficient resource management policies such as follow-the-sun (aimed at exploiting renewable energy sources to the extent possible) and cloud bursting are two illustrating use cases [11] .

A sixth use case is vendor lock-in. Cloud customers currently face vendor lock-in issues in re-targeting their distributed applications from one cloud provider to another. A cloud-agnostic checkpointing service would overcome heterogeneity issues and empower cloud users to take advantage of the competitive cloud computing market by outsourcing their applications to another provider.

Last but not least is the seventh use case. Migrating legacy distributed applications to the cloud remains a tedious task for users who don't have system administration skills. In the context of IaaS clouds, porting from a cluster to a virtual cluster in the cloud may require the skills of a system administrator and the domain-specific knowledge of an end-user. The portable checkpointing service proposed here is a key building block for a *cloudification* service, significantly reducing the burden of legacy applications users in moving their application to the cloud. In principle, a user would simply use the CACS-based cloudification service to migrate her application from her desktop or local cluster to a selected IaaS provider, since the design of CACS will extend to run on other resource management services, including a Linux desktop system and the resource management system (RMS) (e.g., batch system) of an HPC cluster.

There is no claim that the current CACS design will satisfy all of the above use cases. Some use cases might require specialized cloud configurations or specialized data services [12].

III. DESIGN PRINCIPLES OF CACS

To address the requirements presented in the previous section, we developed a Cloud-Agnostic Checkpointing Service. We discuss five principles that guided its design.

A. Why Using a Process-level Checkpointer rather than VM Snapshots?

A key design principle of the Cloud-Agnostic Checkpointing Service is that it leverages a process-level checkpointer for checkpointing distributed applications executed in virtual machines. There are two primary reasons why a process-level checkpointer was chosen instead of using the VM snapshot mechanism offered by hypervisors. First, snapshotting a set of virtual machines is more expensive than checkpointing a set of processes. In the latter case the operating system is not checkpointed, and the checkpoint size is much smaller. While data deduplication techniques [11] can be used to reduce the cost of live migration, our approach has a broader applicability being hypervisor-agnostic.Second, process-level checkpointers like DMTCP manage dependencies among communicating multithreaded processes when saving a checkpoint. When checkpointing a distributed application running in multiple VMs using VM snapshots, hypervisors fail to handle the inter-process communications of distributed processes.

VM snapshots have been extensively used to checkpoint an application running in a single VM, since it provides a generic checkpointing mechanism transparent to the application, which does not need to be modified. A process-level checkpointer like DMTCP is fully transparent to the application and generic, including support for checkpointing sets of communicating multi-threaded processes. Moreover, in an environment of multiple heterogeneous clouds, a process-level approach to checkpointing the distributed applications of a virtual cluster provides better portability and interoperability than one based on VM snapshots. This avoids the difficulty of porting VM images and adapting to multiple IaaS cloud management APIs, when dealing with different cloud management systems.

B. Eliminating the Checkpoint Management Burden

Checkpointing should come as a service, implying a minimal burden for users. In our approach, users request their VMs from CACS rather than directly from the IaaS cloud manager, and submit their application to CACS while specifying the checkpointing policy (e.g., checkpoint frequency). CACS obtains the VMs, installs and configures the process-level checkpointer and the application inside the VMs, and then automatically triggers checkpoints according to the user-defined policy.

C. Portability and Interoperability

CACS has been designed to execute on top of unmodified existing IaaS cloud management systems, to address a broad IaaS cloud market. Thus, it relies on the de facto standard APIs offered by most IaaS clouds systems, namely EC2 for VM and S3 for storage management.

An important requirement is to be able to detect failures at the level of the server, the VM and the application, within the underlying IaaS cloud management system. For instance, OpenStack does not provide an API to report infrastructure failures to clients. So CACS must include a cloud-agnostic monitoring system. Yet at the same time, CACS should be able to exploit any existing monitoring mechanisms of the underlying IaaS cloud where they exist, as in the case of the Snooze VM management system.

Another portability issue arises from the fact that different IaaS management systems may use different VMI formats and offer different types of VM. This further motivated the first design decision: to use application-level checkpointing rather than VM snapshots.

D. Scalability

CACS should scale with the number of concurrent VMs so that it can be used to tolerate failures in data centers; and it should scale with the size of the applications (with the number of VMs per application) so as to have a limited impact on the execution time of large distributed applications.

The choice of implementation for stable storage has an important impact on these two types of scalability. Thus, CACS relies on distributed parallel file systems such as Ceph [13] in order to cope with the huge volume of data to be stored when several checkpoints are taken simultaneously. Similarly, efficient VM management is also essential to limit as much as possible the recovery time.

E. Usability

Nowadays, providing a REST API for a service is a key feature. Resources are served using various server representations. This eases the interaction with users and with third-party software (e.g., CLI, web-based GUI). Moreover, the statelessness of server requests in a REST API provides for server scalability, since communication between clients and server is loosely coupled.

IV. OVERVIEW OF CACS

Next, the CACS architecture and its core components are presented. First, the underlying technology, DMTCP, is introduced. Then the CACS internal components are examined.

A. DMTCP Application Checkpointer

The choice of DMTCP (Distributed MultiThreaded CheckPointing) [1] for checkpoint-restart was dictated by the maturity of that ten-year old project [14] available as binary packages for Debian/Ubuntu, Fedora/CentOS/Scientific Linux/Red Hat, and OpenSUSE). In particular, DMTCP supports the types of migration of processes among heterogeneous environments that were described in Section II.

In DMTCP, each application is associated with a unique DMTCP application coordinator in charge of coordinating the checkpointing of processes running on distinct computer nodes. The coordinator need not reside on a host that is hosting application processes, and directly communicates with DMTCP daemons running on each node hosting application processes. When an application is restarted, a new DMTCP coordinator is used, thus avoiding any single point of failure.

B. Architecture of CACS

Figure 1 depicts the overall architecture of the service. The *RESTful API* allows users to manage their applications and their corresponding checkpoints. The *Coordinators Database* stores all the applications information. The *Application Manager* orchestrates application management (start and restart) and enforces failure recovery mechanisms. It communicates with the *Cloud Manager* to manage (create, destroy) virtual clusters. The Cloud Manager interacts with the underlying IaaS cloud system to manage the VMs. The *Provision Manager* takes on the burden of efficiently configuring the virtual clusters. The *Checkpoint Manager* component is for managing the application checkpoint images. The *Monitoring Manager* component enables VM and application process failure detection. It is notified about application health issues and VM failures by monitoring daemons running in each VM of the virtual cluster executing the application. In the event of a notification, it interacts with the Application Manager in order to stop and/or recover the application from a previous checkpoint.

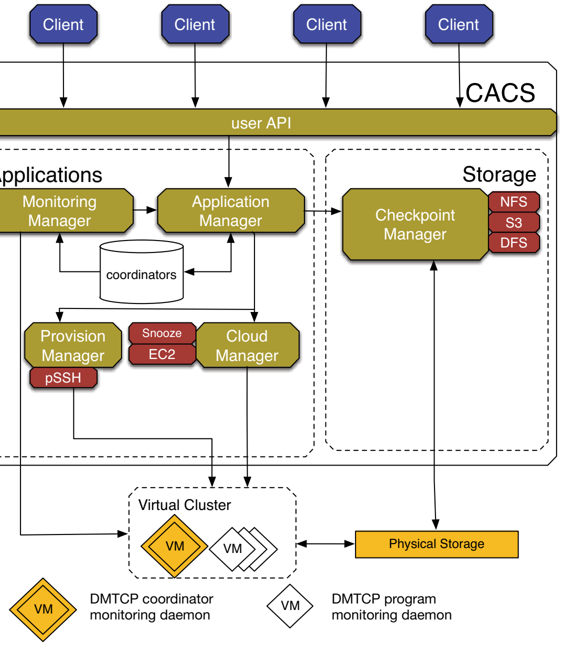


Fig. 1: Cloud Checkpointing Service Architecture

An application is executed under the control of DMTCP whose daemons run in each VM hosting the application processes, with one of them running the DMTCP coordinator.

V. TYPICAL SCENARIOS

We describe five scenarios of a typical CACS user, ordered according to the life cycle of an application comprising of n processes running in n different virtual machines. This section describes in greater details some mechanisms used to handle user requests. Table I depicts the description of the resources managed by the API and the available operations.

`coordinators resource`	
GET /coordinators	returns the list of coordinators known by the system
POST /coordinators	add a new coordinator to the system
`coordinator resource`	
GET /coordinators/:id	returns the information of the coordinator with id : id
DELETE /coordinators/:id	delete the coordinator
`checkpoints resource`	
GET /coordinators/:id/checkpoints	returns the list of the checkpoints of the coordinator
POST /coordinators/:id/checkpoints	trigger a checkpoint for the coordinator or upload a checkpoint image
`checkpoint resource`	
GET /coordinators/:id/checkpoints/:id	returns the information of a checkpoint
POST /coordinators/:id/checkpoints/:id	restart the coordinator from the checkpoint
DELETE /coordinators/:id/checkpoints/:id	delete the checkpoint

TABLE I: REST API description

A. Application Submission

Here we describe application submission to CACS. A POST request is issued to the `coordinators resource` and the body contains the representation of an *Application Submission Request (ASR)*. The ASR encapsulates the VM templates and the configuration parameters of DMTCP needed to start the application.

Once the Application Manager validates the ASR, the application enters the CREATING phase (see Figure 2) during which virtual resources are claimed by the Cloud Manager. Once the VMs have been given to the computation, the PROVISION phase starts. In this phase, the Provision Manager remotely executes specific commands to prepare the computation to be run. The provision includes internal actions (e.g., creation of checkpoint directory in the VMs) but also user-defined configuration (e.g., periodicity of the checkpoints, specific initializations). The provisioning phase may differ according to the storage back-end used.

The READY state is introduced to reflect the fact that all the VMs are ready to start the computation. The RUNNING state indicates that the computation is in progress. In this phase, checkpoints can be saved.

An alternative way of starting an application is described in section V-C.

B. Saving Checkpoints

Three modes of transparent checkpointing are supported: (1) user-initiated checkpointing; (2) periodic checkpointing; and (3) application-initiated checkpointing (for example, at the end of each application iteration). The first case can be fulfilled by issuing a POST request to the corresponding `checkpoints resource`. In the second and third case, DMTCP triggers the checkpoint without the need for a POST request. CACS distinguishes between local and remote storage. Where fast local storage is available (e.g., a local disk, an SSD, or a RAM disk inside RAM itself), the checkpoint image is written first to the local storage. For redundancy, it is also copied (on a lazy basis) to remote storage, such as Ceph and NFS.

C. *Application Recovery, Cloning and Migration*

The API enables the following scenarios: (1) application restarting (the application state is reset to a previous checkpointed state and restarted); (2) application cloning (a new application is created and restarted from a previous checkpointed state of the original application); and (3) application migration (an application is cloned to another cloud and terminated on the source cloud).

In the first case, metadata for the checkpoints is retrieved from the Checkpoint Manager. Then the Application Manager triggers a *passive recovery mechanism*: new VMs can be restarted and provisioned if some VMs of the original set are not reachable any more. Finally each VM in the computation downloads its corresponding checkpoint images from the storage. The process of restarting the application is delegated to DMTCP.

Cloning and migrating provide alternative ways of creating an application. In these cases, a new application is created by issuing a POST request to the `coordinators resource`. Second, n POST requests are sent to the corresponding `checkpoints resource` to upload a set of checkpoint images. Finally, a POST to the `checkpoint resource` will restart the application. This will trigger the *passive recovery mechanism* to generate a new virtual cluster where the application will run.

D. *Application Termination*

Terminating an application consists of removing all references to the application in the system. This can be decomposed as: (1) deletion of the corresponding entry in the *coordinator database*; (2) removal of all the stored checkpoint images from the storage; and (3) release of the allocated VMs back to the pool of idle VMs in the underlying infrastructure.

The TERMINATING state is reached when an end user issues a DELETE request to the `coordinator resource` or when the ERROR state is set for the application.

VI. IMPLEMENTATION OF CACS

This section describes in detail some technical aspects of CACS.

A. *Cloud Manager*

The current CACS prototype supports two underlying IaaS technologies (Snooze and EC2 compatible VM management systems) allowing us to demonstrate the portability and interoperability of CACS in heterogeneous cloud environments. Snooze [7] is a scalable highly available system. It has been primarily designed as a small system easing the deployment of VMs and easing experimentation with VM management strategies. The Cloud Manager uses the specific REST API of Snooze to manage virtual clusters. Snooze provides a server and VM failure notification API that can be directly used by the Monitoring Manager. (Thus with Snooze, no monitoring daemons need to be executed in the VMs.) EC2 compatible Cloud (like Openstack [3]) are supported as well. OpenStack does not provide a failure notification interface and thus the cloud-agnostic monitoring service is used.

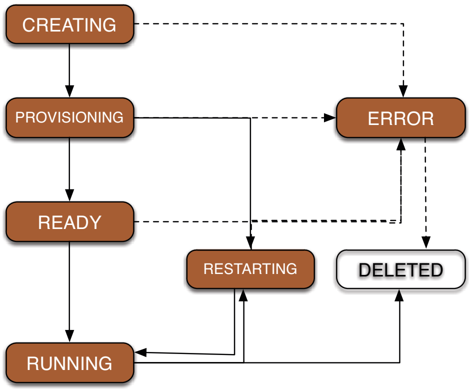


Fig. 2: CACS Coordinator states

B. *Checkpoint Manager and Storage System*

The Checkpoint Manager, depicted in Figure 1, enables different storage systems to be plugged into CACS. The current implementation of the service is stateless and supports two storage systems: (1) NFS and (2) S3. NFS is suitable for small-scale deployment and especially for prototyping. S3 is the *de facto* standard API of Amazon Web Service for manipulating stored objects. Supporting S3 gives CACS compatibility with the major Cloud providers, but also with other solutions such as Ceph.

Since checkpoint images may be generated periodically, under application control, or by the end user, a decision was made to save checkpoint images asynchronously. The Checkpoint Manager is not aware of the existence of checkpoint images until a restart is required. At that time, the Checkpoint Manager will choose the most recent checkpoint image, by default, but a user may also specify an earlier image.

C. *Monitoring Manager*

Some cloud platforms support an external API for monitoring if the VMs are alive. However, those cloud-specific mechanisms are not sufficiently flexible. Our goals are threefold: (1) being cloud-agnostic; (2) testing the liveness of the VMs; and (3) testing the "health" of the application.

The concept of health is application-specific. An application may fail due to unreachability of a computer node, insufficient memory, internal busy waiting within an application, bugs in the application code, issues induced by the execution context, the reception of spurious signals such as SIGCHILD and SIGPIPE, and a myriad of other causes. A user-defined application-specific routine can define and test the application's health using a function hook offered by CACS.

The current implementation is based on a binary broadcast tree for each application. Each node of the broadcast tree is represented by a daemon, which calls the user's hook function to determine if the processes on that node are healthy. A standard broadcast tree then allows the root node to report a list of nodes that are unhealthy or unreachable to the Monitoring Manager. If problems are reported, the Monitoring Manager interacts with the Application Manager to trigger an application recovery.

There are two cases:

1) *VM failure:* A VM is unreachable. CACS reserves a new VM from the underlying cloud infrastructure and restarts the application from a previous checkpoint.
2) *Application failure:* If all VMs are reachable, the application itself may still be reported as unhealthy. As an optimization, one then kills the processes of the application within their VMs, and restarts the application processes within their *original* VMs.

D. Resilience: Avoiding Single Points of Failure

CACS should be resilient to node failures. Its managers are stateless thus they can be easily restarted in the event of a failure. For purpose of high availability, traditional server replication and failover approaches leveraging Apache Zookeeper [15] can extend the current design. The coordinators database could be implemented relying on a NoSQL reliable distributed database technology such as Cassandra or MongoDB that does not exhibit any single point of failure. The stable storage properties of the checkpoint storage are guaranteed through the use of a fault-tolerant distributed file system (e.g. Ceph) that provides persistent and highly available storage.

The Snooze IaaS cloud management system has been designed to be highly available in the event of simultaneous failures [7]. Nevertheless, it does not ensure automatic recovery of virtual clusters in the event of the failure of the server hosting one of their VMs. By integrating CACS in Snooze, computations running in virtual clusters can be automatically restarted in the event of a failure. Users of the enhanced Snooze system can enjoy both reliable application execution and a highly available IaaS cloud tolerating multiple simultaneous failures of physical machines hosting VMs and/or VM management services.

E. Other Implementation Details

CACS is implemented in Java and makes use of the scalable RESTlet [16] framework to expose its API. The user requests are mostly treated in background using a pool of threads to optimize the parallelization and the responsiveness of the API. In the current implementation the coordinators database is stored in memory. The provision manager uses parallelization of SSH connection, to act on virtual clusters.

VII. EXPERIMENTAL EVALUATION

The experiments are divided into four parts: scalability with application size up to 128 nodes using Snooze as a testbed (Section VII-A); resource consumption of CACS, including the performance of the monitoring system (Section VII-B); a performance study of migration between different clouds or between desktop and cloud (Section VII-C); and a study of the cloud-agnostic feature of CACS as applied to Snooze and OpenStack (Section VII-D).

The evaluation of the system was conducted on the Grid'5000 [17] testbed. A typical workflow for experimenting on the platform is to reserve physical nodes, then to deploy a Linux-based environment, and finally to deploy and configure the desired software stack. The Debian Wheezy distribution (3.2.0-4-amd64 Linux kernel) served as the base environment for deploying Snooze (version 2.1.6) and Ceph storage (Firefly). Ubuntu 12.04 (kernel version 3.2.0-24-generic) was used for deploying Openstack (Icehouse). On the two clouds we used an Ubuntu 13.10 x86_64 base image, preconfigured with the DMTCP distribution (version 2.3). Both clouds use KVM/QEMU.

A. Scalability with Application Size

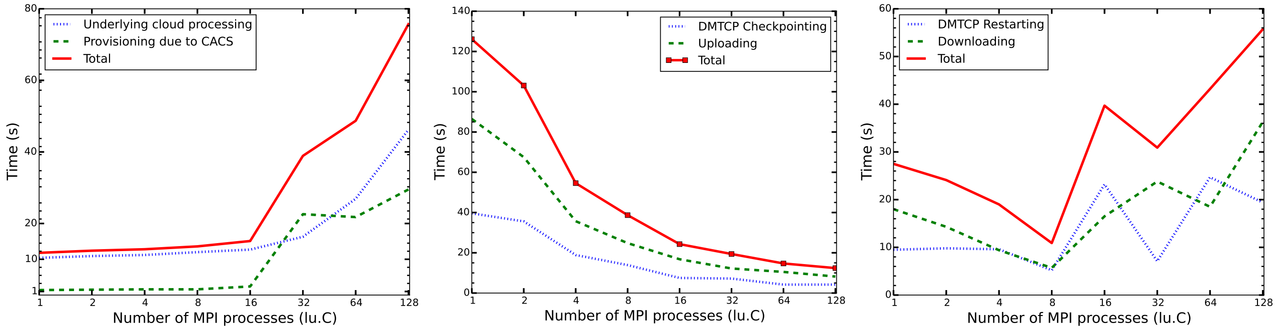
The scalability test was conducted using Snooze configured with more than 400 vCPUs and nearly 1 TB of memory available, enough for holding more than 128 virtual machines, each of which requires one virtual core and 2 GB of memory. The NAS MPI test for LU (Class C) was employed [18]. Each MPI ran on a separate VM. We measured the performance for three phases: time to finish the application submission, time to perform a checkpoint, and time to perform a restart. Figure 3 shows that creation of the VMs and execution of commands (provisioning, checkpoint, restart) require significant time. Time for submission depends strongly on the underlying infrastructure used (see Section VII-D for more details), while the latter two times are related to the number of VMs involved in the application.

Figure 3a shows the performance for application submission, which includes two steps: the underlying cloud allocates the VMs; and CACS provisions the VMs. The proposed CACS implementation optimizes the command execution mechanism through: (1) the parallelization of the SSH connections; and (2) re-use of the connections of the open SSH sessions. As a result, increasing the number of nodes increases only slightly the time for executing commands, up until the configured maximum limit of SSH connections is reached. This occurs after 16 nodes in the current setup.

Number of processes	1	2	4	8	16
Ckpt size (MB)	655	338	174	92	49

TABLE II: Checkpoint image sizes for the NAS benchmark lu.C, under different configurations. The checkpoint image size is for a single MPI process.

The time for a single checkpoint is shown in Figure 3b. Also, Table II shows the checkpoint image size as the number of nodes varies. Here, the primary workload contains two parts: DMTCP writes the checkpoint image to local storage; and each VM uploads the image to the remote file system. Figure 3c illustrates the performance for restart. In this case, the trend becomes unstable for a large number of nodes. This is due to network traffic when all nodes try to simultaneously download the checkpoint images. As a consequence, restarted processes do not join the computation concurrently, leading to jitter and less reproducible timings for DMTCP restart.



(a) Submission time

(b) Checkpoint time

(c) Restart time

Fig. 3: CACS over Snooze

B. Resource Consumption and Monitoring System

This section focuses on the resource consumption of CACS, as well as the performance of the monitoring system. They share the same experimental configuration: for Snooze, 7 servers hosting VM management services and 12 servers hosting VMs (264 cores in total) were deployed. The target application used was *dmtcp1*, a single-process lightweight application found in the DMTCP test suite [1].

1) Resource Consumption of the Service

In this experiment, 100 applications were submitted to CACS, with one new application submitted every second. The network consumption and memory usage are shown in Figure 4a and Figure 4b, respectively. The vertical line at 100 seconds shows when the 100 applications had been submitted, but were not necessarily executing yet. Both figures show a decreasing trend as processing continues.

Figures 4a and 4b can be understood better through a review Of the CACS implementation. CACS maintains a thread pool to handle incoming submissions. Theoretically, it can concurrently handle as many applications as there are threads in the thread pool (100 in this experiment). But the underlying cloud infrastructure has its own limitations: most clouds can handle only a relatively small number of applications concurrently.

The linear decline in network bandwidth observed after the vertical line in Figure 4a can be explained as follows. Assume that the cloud can handle n submissions concurrently, implying that there are n threads running SSH commands on the VMs provided by the cloud. Meanwhile, there are m threads polling the cloud front-end as it causes the VMs to be built. Assume also that the network bandwith consumed by a polling thread and an SSH thread are both constants, namely, c_1 and c_2. Based on these assumptions, we conclude that at any given time, the network traffic is:

$$mc\_1 + nc\_2.$$

In our case, m is initially 100. Since VMs are processed at a uniform rate, m will decrease at a uniform rate, thus explaining the linear trend in Figure 4a. A similar analysis also explains the decreasing trend seen in Figure 4b.

2) Performance of the Health Monitoring System

The health monitoring system was discussed in Section VI-C. To measure its performance, we submitted applications with varying numbers of VM requests, and recorded the time required to finish one round-trip for a heartbeat (employing the binary broadcast tree described earlier). Figure 4c shows the result: the time to finish one heartbeat round-trip is logarithmic in the number of nodes, as expected. This provides strong evidence that the broadcast tree implementation consumes few network resources and scales to support large distributed applications.

C. Migration Evaluation

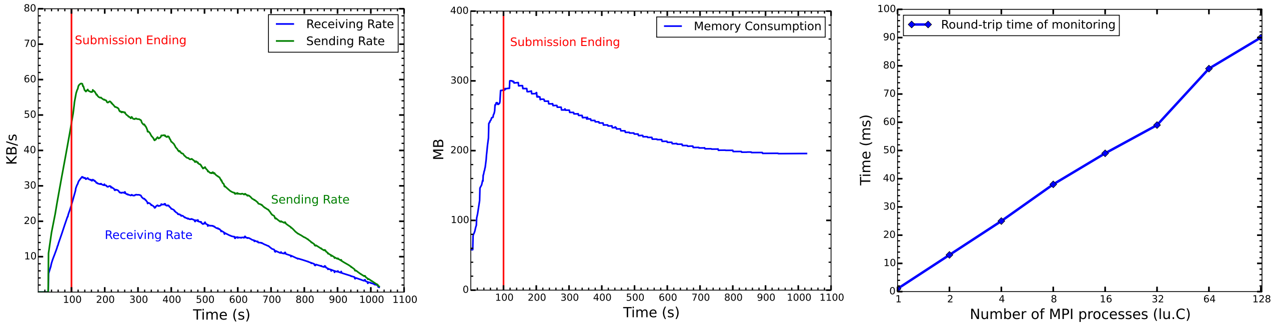
Migration of distributed applications are important in the real world. CACS is evaluated in two migration scenarios. Section VII-C1 evaluates the *cloudification* of an NS-3 [19] application. NS-3 simulations are known for requiring long periods of time, and thus are good candidates for migration from commodity hardware to the cloud. Section VII-C2 demonstrates the migration of applications between two distinct clouds: Snooze and OpenStack.

1) From Hardware to Cloud

Cloudification refers to migrating a conventional desktop or laptop application to the cloud. Statistics were obtained for migrating an NS-3 application from a physical machine to the OpenStack destination cloud. The target application was *tcp-large-transfer* from the NS-3 distribution. The parameters of the application were set to simulate a 1 Gb transfer rate transferring 2 GB of data over a period of 30 seconds. The application was checkpointed after 10 seconds. A 50-line Python script invokes CACS, which checkpoints on the current machine and restarts in the destination cloud. The application contains a single process and the checkpoint image was approximately 260 MB Application restart on OpenStack required 21 seconds. Note that in the destination cloud none of the VMs have NS-3 installed. DMTCP checkpoint images include a copy of the memory of the process. Since the NS-3 libraries were already present in memory, they were transported to the destination cloud as part of the checkpoint images.

2) From Cloud to Cloud

Next, application migration between Snooze and OpenStack was studied. Two instances, CACS-Snooze and CACS-Openstack, were deployed each relying on its corresponding IaaS platform. The target application is dmtcp1, the same as in



(a) Network bandwith

(b) Memory consumption

(c) Performance of the monitoring system (Note: logarithmic x-axis)

Fig. 4: CACS resource evaluation

Section VII-B. 40 different instances of the application were incrementally started on CACS-Snooze and then cloned to CACS-OpenStack using a 90-line Python script. The script checkpoints on the current cloud and restarts on the destination cloud. The experimental setup used a single instance of Ceph-based storage for both services, since both clouds were deployed on Grid'5000. Alternatively, two distinct storage systems could have been used as well with no modification. The application checkpoint periodicity was set to 60 seconds. The checkpoint image sizes were approximately 3 MB each.

Figure 5 depicts the overall network utilization at the storage level. It shows a linear increase of network utilization after start of the submissions. A plateau indicates that the applications' checkpoint images were received and stored and no submissions remain. The migration phase lasts for 2.5 minutes. The network utilization during this phase increases due to the data transfer of the checkpoint images. Note that the time to transfer checkpoint images from CACS-Snooze to CACS-OpenStack is negligible in this case, due to the small size of the checkpoint images. The network utilization then reaches another plateau, indicating that two instances of each application are now running on the two different clouds (80 applications in total). After a certain period of time, all applications are terminated.

The experiment also demonstrates the ability of CACS to handle numerous concurrent restart requests (up to 40 requests).

D. Comparison of Different IaaS Technologies

Next, we compare the performance of CACS, when targeted toward two distinct cloud management systems: Snooze and OpenStack. The configuration for Snooze is the same as in Section VII-A, while OpenStack is configured with the same computing resources. Figure 6 reports the submission times, including both the time for the IaaS to process the VM submissions, and the time for CACS to provision the VMs. Figure 7 reports the checkpoint and restart times. Note that the same checkpoint policy was used for both clouds. Hence, the checkpoint sizes are the same (see Table II). This implies that the uploading time during checkpoint and the downloading time during restart should be comparable, except to the extent that different network traffic conditions exist during the two phases. For this reason, Figure 7 reports a single time for checkpoint/restart, since the times for checkpoint and restart are comparable.

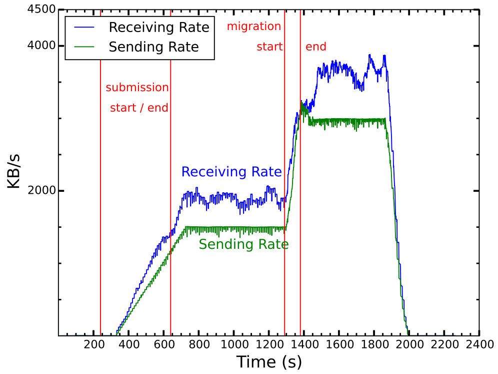


Fig. 5: Migration performance of 40 applications

Figure 6 shows that although the underlying IaaS systems are different, the time for CACS to provision the VMs remains comparable. In contrast, the time for different IaaS systems to process VM allocation differs greatly. The preceding breakdown into CACS-specific and IaaS-specific times illustrates that CACS is able to support different cloud management systems, with little or no CACS-specific difference in performance.

Figure 7 shows a similar trend, except that the restart time for OpenStack is not stable. This occurs for a pragmatic reason: normally, OpenStack recommends that network management and applications be located on different networks. However, the limitations of the Grid'5000 testbed forced the placement of both types of network data onto the same network. This leads to data variability, as seen in the figure.

VIII. RELATED WORK

We first review previous work on application checkpointing and virtual machine snapshot mechanisms. We then study existing approaches for reliable application execution in clouds.

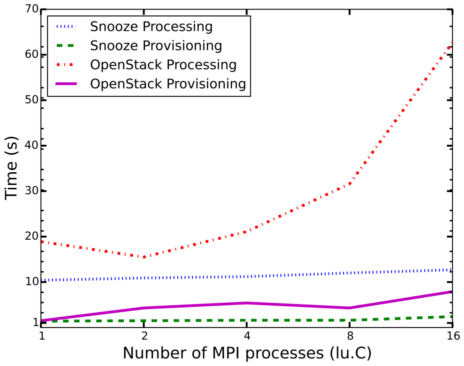


Fig. 6: Comparison of submission time

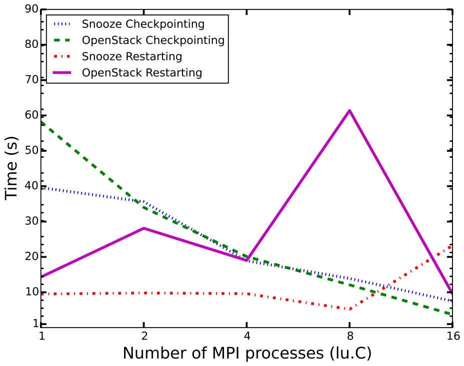


Fig. 7: Comparison of Checkpoint/Restart time

A. *Options for Checkpointing Distributed Applications*

In addition to DMTCP, several other checkpointing packages are in common use today. The survey [20] describes several checkpoint/restart implementations for high performance computing. More generally, we review the checkpoint-restart packages in widespread use today.

For distributed computation, most checkpointing services today were built around MPI-specific checkpoint-restart services. Unfortunately, this was not an option for the current work, since a cloud-agnostic checkpointing service must also be application-agnostic. Nevertheless, historically there has been much effort toward MPI-specific custom checkpoint-restart service. This came about when InfiniBand became the preferred network for high performance computing, and there was still no package for transparent checkpointing over InfiniBand. Examples of checkpoint-restart services can be found in Open MPI [21] (CRCP coordination protocol), LAM/MPI [22] (now incorporated into MVAPICH2 [23]), and MPICH-V [24]. Each checkpoint-restart service disconnected the network prior to checkpoint, called on a single-node checkpointing package such as the kernel-based BLCR [25], and then re-connected after restart.

The current work is based on a new approach, implemented within DMTCP, which enables transparent checkpointing over InfiniBand [2] as well as over TCP. This uniformly supports both MPI and other distributed applications.

B. *Mechanisms Based on VM Snapshots*

VM snapshots provide an alternative for checkpointing. The well-known packages KVM/QEMU, VirtualBox, and VMware all support snapshots of VMs. However, the choice of a particular VM for a particular cloud platform is contrary to the goal of a cloud-agnostic service in this work. Furthermore, saving just the application is more efficient than saving an entire VM, in part due to the smaller memory footprint of a bare application.

C. *Fault Tolerance and Efficiency in the Cloud*

There exist several alternative approaches to fault tolerance in the Cloud. Tchana et al. argue for shared responsibility between provider and user [26]. Zhao et al. follow a middleware approach [27]. Egwutuoha et al. take a process-level redundancy approach [28]. Di et al. present an adaptive algorithm to optimize the number of checkpoints for cloud-based applications [29].

Nicolae et al. show how to checkpoint an MPI application using distributed VM snapshots using the BlobSeer distributed repository [30]. This approach is MPI-specific, since it employs the MPI checkpoint-restart service with BLCR. (See Section VIII-A for a discussion of MPI checkpoint-restart services.) Kangarlou et al. [31] and Garg et al. [32] each show how to take a distributed snapshot of VMs. Kangarlou et al. base this on a modification of Xen's live migration, while Garg et al. employ DMTCP to take a distributed snapshot of KVM/QEMU VMs. The last three investigations ([30], [31], [32]) contrasts with the cloud-agnostic (and application-agnostic) approach employed here by directly checkpointing the processes along with their network connections.

Several works study detection of failure modes [33], [34]. The approach of the Gamose system [35] for monitoring the health of Grid applications can extend the CACS checks for application health without requiring application hooks. Such a system relies on interposing on systems calls, and does not require any modification to the operating system.

The work of Marshall et al. [10] demonstrates the utility of backfill VMs in maintaining a high utilization rate for the processors of the cloud. The backfill VMs can be combined with a checkpointing policy so as to always guarantee a supply of checkpoint images that can be restarted on demand to instantiate the backfill VMs.

IX. CONCLUSION

The Cloud-Agnostic Checkpointing Service demonstrates checkpointing as a service on top of heterogeneous IaaS cloud systems in an environment of multiple heterogeneous clouds. A key design principle of CACS is that it is built around the DMTCP mechanism for taking checkpoints of distributed processes, rather than employing distributed VM snapshot mechanisms. This creates a cloud-agnostic service that is independent of the cloud platform, and independent of the cloud's choice of virtual machine technology. Preliminary experimental evaluations demonstrate portability between two IaaS cloud management systems and demonstrate scalability with the number of applications and the application size. CACS also supports migration between heterogeneous clouds, and *cloudification*, migration from a traditional environment to the cloud. In our next steps, we will further improve the scalability of CACS, study its efficiency in different computing environments varying the resource, VM and storage management systems, and experiment with a broader range of distributed applications.

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