An ontology for heterogeneous resources management interoperability and HPC in the cloud

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HIGHLIGHTS

• An ontology for interoperability in heterogeneous cloud infrastructures is proposed.
• Enable the adoption of heterogeneous physical resources in self-managed clouds-Support for HPC-in-Cloud, hardware accelerators, resource abstraction methods.
• A proposed architecture to exploit the semantic and syntactic benefits.
• Included into the CloudLightning project for large scale Cloud Computing environments.

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ABSTRACT

The ever-increasing number of customers that have been using cloud computing environments is driving heterogeneity in the cloud infrastructures. The incorporation of heterogeneous resources to traditional homogeneous infrastructures is supported by specific resource managers cohabiting with traditional resource managers. This blend of resource managers raises interoperability issues in the Cloud management domain as customer services are exposed to disjoint mechanisms and incompatibilities between APIs and interfaces. In addition, deploying and configuring HPC workloads in such environments makes porting HPC applications, from traditional cluster environments to the Cloud, complex and ineffectual.

Many efforts have been taken to create solutions and standards for ameliorating interoperability issues in inter-cloud and multi-cloud environments and parallels exist between these efforts and the current drive for the adoption of heterogeneity in the Cloud. The work described in this paper attempts to exploit these parallels; managing interoperability issues in Cloud from a unified perspective. In this paper the mOSAIC ontology, pillar of the IEEE 2302 — Standard for Intercloud Interoperability and Federation, is extended towards creating the CloudLightning Ontology (CL-Ontology), in which the incorporation of heterogeneous resources and HPC environments in the Cloud are considered. To support the CL-Ontology, a generic architecture is presented as a driver to manage heterogeneity in the Cloud and, as a use case example of the proposed architecture, the internal architecture of the CloudLightning system is redesigned and presented to show the feasibility of incorporating a semantic engine to alleviate interoperability issues to facilitate the incorporation of HPC in Cloud.

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1. Introduction

Cloud computing environments offer customers a wide diversity of services through loosely coupled instances, and storage systems, guaranteeing certain levels of services. Features such as availability on demand, large capacity, elasticity, and service-level performance have been attracting end-users to migrate (to Cloudify) their applications from traditional cluster environments.

It is estimated that by the year 2019 more than 85% of workloads will be processed by Cloud environments [1].

The Cloud market is expanding [2,3] and this growth is attracting specific users demanding specific services that are driving the traditional homogeneous Cloud infrastructure to become a heterogeneous ecosystem. In particular, supporting High Performance Computing (HPC) services in the Cloud requires an evolution of the traditional homogeneous cloud [4]. HPC as-a-service (HPCaaS) is leading the availability of services that, from a cloud management perspective, are challenging to support. Cloudifying HPC applications while maintaining performance, while desirable,
The main goals of this work are: to create an ontology, known as the CloudLightning Ontology (CL-Ontology) that supports heterogeneous and high performance resources in the Cloud; to ameliorate interoperability issues between existing resource managers and resource abstractions; to maintain compatibility with previous standards for interoperability.

The CL-Ontology extends the IEEE-2302 (SIIF) — Standard for Intercloud Interoperability and Federation [22], and the IEEE-2301, Guide for Cloud Portability and Interoperability Profiles (CPIP) [23]. This extensions incorporate support for resource management, specific hardware accelerators, and different resource abstraction methods, such as virtual machines and containers into the Cloud; matching service requests to specific heterogeneous infrastructures, and enabling intelligent resource discovery. To the best of our knowledge this is the first attempt to explicitly address an Ontology supporting HPC in Cloud.

In addition to the CL-Ontology, in an effort to demonstrate its utility, this paper presents a conceptual Service Oriented Architecture (SOA) for autonomic resource management. In the proposed architecture, the CL-Ontology is used as part of a semantic engine to dynamically incorporate resources into the cloud resource fabric, and to support decisions making for targeting service requests to appropriate resources. Finally, the architectural design of the CloudLightning [24,25] (EU H2020-ICT programme under grant #643946) system is presented as use case into which the proposed semantic engine is incorporated, and where the management of heterogeneous resources at scale is undertaken.

2. Related work

Many efforts have been made towards addressing interoperability issues in the Cloud by creating common interfaces and APIs that enhance the compatibility between deployment models and public vendors. The Open Cloud Manifesto [26] is an initiative by industry for supporting open standards in cloud computing. The main targets are grouped into five categories: security, data application interoperability, data application portability, monitoring and portability between clouds. However, the Manifesto does not incorporate current cloud technologies nor support hardware accelerators within any of the above mentioned categories. Similarly, the Universal Cloud Interface (UCI) [27,28] was proposed to solve inter-cloud interoperability avoiding lock-in issues with proprietary solutions by unifying the representation of all cloud resources in a common interface. Its evolution has been very limited and UCI does not incorporate concepts emerging from cloud technologies.

The Guide for Cloud Portability and Interoperability Profiles (CPIP) [23] assist cloud computing vendors and users in developing, building, and using standards/based cloud computing products and services. For each element, multiple options are proposed regarding interfaces, file formats and operational conventions. However, these are grouped in the “Standard profiles”, as drivers for interoperability from a user perspective, does not support concepts on specialized hardware nor emerging resource abstraction methods in Cloud.

Another initiative, specifically targeting the IaaS service model, is the Open Cloud Computing Interface (OCCI) [29]. OCCI defines an interface to support the creation of hybrid cloud environments independently of cloud providers and frameworks. It specifies, in UML, real-world resources and their links, expressed in a similar manner to an OWL [30] ontology definition. However, OCCI targets a user-view perspective of the Cloud, in which resource managers manage traditional homogeneous resources, and hence, do not address interoperability issues caused when multiple services coexist and use diverse abstraction methods and specialized hardware.

By using ontologies, it is possible to generate intelligent decision support mechanisms for addressing interoperability issues in
services-based architectures. Accordingly, ontologies have already been used in the HPC arena. Zhao et al. [31] created an HPC ontology exposing the lack of a flexible and open infrastructure for the HPC community to effectively share, accumulate, and reuse knowledge. Although the authors emphasize the design of an HPC ontology, their work is in an early stage. Another ontology in HPC computing is proposed by Tenschert A. in [32], describing a matching method for decomposing HPC applications into distributed environments by using an HPC ontology. However, the main goal of the authors is to decompose applications between compute and data processes for HPC environments, rather than cloud environments.

Cloud ontologies have been widely used in recent years. Imam F. describes in [21] well-known applications of Ontologies to Cloud Computing. These are grouped into security [33], resource management and service discovery [34,35], and interoperability categories. The most remarkable work in the interoperability category is the mOSAIC cloud ontology [36], showing a detailed and simple description of cloud computing resources. This ontology has been developed in the mOSAIC project within the European framework FP7 and is targeted to promote transparency in multiple clouds accesses. For its development both, the taxonomy proposed by the National Institute of Standards and Technology (NIST), and the IBM Cloud computing Reference architecture were extended, for the later incorporation to the Guide for Cloud Portability and Interoperability Profiles (CPIP) IEEE-2301 [23]. Thus, mOSAIC ontology is currently part of the standard SIIF-IEEE P2302 [22], addressing inter-cloud interoperability from the user interaction perspective, providing detailed entities for SLAs and Interfaces/APIs. Moreover, the ISO–IEC JCT 1, Standard in Cloud computing and Distributed Platforms [37] focuses on the standardization for interoperable distributed application platforms and web services, service oriented architectures, and cloud computing. Specifically, the ISO/IEC 18384 [38] uses ontologies to describe actors, services consumers, services providers, and legal aspects of the Cloud. However, recent advances in technology, hardware accelerators, resource managers, and resource abstraction methods required to avoid interoperability issues arisen from the incorporation of heterogeneous resources into Cloud, are not part of these standards.

Other initiatives in the EU frameworks FP7 and H2020 targeting interoperability and lock-in vendor issues in cloud computing environments have been explored. Foremost among these are: Cloud4-SOA [39], a platform that performs seamless adaptive multi-cloud management, semantically interconnecting heterogeneous PaaS offerings across different cloud providers, and the same technology and supported by Apache Brooklyn blueprints and TOSCA extensions; PaasSport [40] where Cloud PaaS technologies are combined with lightweight semantics and in which application models and SLAs follow a Descriptions and Situations Pattern Technique, used to deliver a thin and non-intrusive Cloud-broker in the form of a Cloud Marketplace; Paasage [41] that constructs a deployment mechanism for applications across public and private clouds constrained by a set of rules described in the CAMEL [42] modeling language; ModaClouds [43] that follows a Model-Driven-Development for Clouds and Multi-Clouds, performing semi-automatic translations into code to enable deployments across public and hybrid cloud vendor platforms; and finally, the Mikelangelo project [44], that provides support for HPC in Cloud environments by implementing a bespoke virtual machine manager to allow the management in of HPC and Cloud resources. Although these projects succeed in exploring different alternatives for interconnecting heterogeneous vendor service offerings, enhancing extant interfaces, or providing decision support systems, either they neglect the incorporation of HPC into the Cloud and the subsequent need for having multiple resource management domains, or they do not support a wider heterogeneous environment, being constrained to only resource management, hardware accelerators, or resource abstractions in the same Cloud.

3. CL-Ontology

The CL-Ontology has been developed to address interoperability in a heterogeneous cloud resource fabric. The basis of the CL-Ontology is the mOSAIC ontology and, although the latter focuses on intercloud/multicloud environments from a SaaS and PaaS perspective, it provides a strong foundation enabling extensions to capture the emerging heterogeneous cloud.

Incorporating HPC environments in the cloud is made possible by extending the interoperability concept considered by the mOSAIC ontology with additional semantics to support: inter/intra-cloud environments, and heterogeneity in the usage of resources, resource managers, and co-processors.

The creation of the CL-Ontology is a methodical procedure for which each extension requires seeking and analyzing classes, concepts, attributes, and characteristic from the mOSAIC ontology to ensure consistency. Moreover, when an element has been added as a new class or subclass, it is necessary to analyze the relationships created between that extension and all of the relevant parts of the base ontology. That analysis unearths issues with relationships, constraints, and restrictions that were unforeseen and unexpected. More detailed information of this process can be found at [45].

The CL-Ontology has been developed in the OWL language by using Protegé 5.2.1 as ontology editor, knowledge management, and visualization system, and used also to generate all Figures included in this section. Finally, for clarity and to distinguish between the original mOSAIC Ontology components (shown as emphasized text), the CL-Ontology extensions are presented highlighted in this section in bold.

1 https://protege.stanford.edu/
3.1. The TopLevel class (∧(owl : Thing))

Fig. 2 depicts the top level of the CL-Ontology. It consists of:
a Language class identifying languages used for API implementations;
a DeploymentModel class, which describes concepts of
classifying features of Cloud systems that users can exploit;
a Framework class supporting programming frameworks;
an Actor class specifying modes of interaction with the Cloud system;
a Property class describing the characteristics of the elements of
Cloud; a ComponentState class identifying concepts for establishing
to the states of diverse Cloud components and resources; a Protocol
class describing communication protocols used in Cloud
environments; a Layers class containing individuals describing firmware,
and software associated to the cloud infrastructure;
a ServiceModels class supporting diversity of services offered in
the Cloud; a CloudSystemVisibility class defining the deployment
models of the cloud computing system; a Component
describing resources, services, and elements part of the Cloud; a Resource-
AbstractionMethods class, previously the Technology class in the
mOSAIC ontology to describe virtualization, and that is extended to
reflect current evolution of cloud ecosystems, supporting also
There Provider class usage, which is a subclass of Actor, has been updated from the offersVirtualMachine to offersResource-
Abstraction, having as subproperties: offerDedicatedResource,
offerVirtualMachine, and offerDockerContainer.

3.2. The Property class

The Property class has FunctionalProperty and NonFunctional-
Property subclasses. The NonFunctionalProperties class describes
or attributes of cloud components, in which following subclasses remain unchanged from the mOSAIC ontology:
Autonomy, Availability, Performance, QoS, Reliability, Scalability
and Security. The CommunicationNonFunctionalProperty, Computing-
NonFunctional, and PropertyDataNonFunctionalProperty classes,
subclasses of NonFunctionalProperties, describe physical features of
processors, communications and storage of resources. However,
the lack of detail for describing hardware accelerators has driven the CL-Ontology to incorporate a CoprocessorNonFunc-
tional class for supporting co-processors and specialized hard-
ware, and hence recognizing heterogeneity in the cloud resource
fabric. Fig. 3 depicts an exploded view of the CoprocessorNon-
Functional class.

3.2.1. The non functional properties class

GPUs, Many Integrated Cores (MICs) architectures, and FPGAs
collectors, have been chosen as co-processors included into
the CL-Ontology as they represent the most part of the market
for HPC in Cloud, however, the CL-Ontology is not limited to
these and can be extended with different existing and future co-
processors using the subclasses of the CoprocessorNonFunctional
class, in which a broad set of specific hardware accelerators can be
uniquely characterized in one of these categories, independently of
the manufacturer and model. It captures heterogeneous hardware
resources being added to the cloud resource fabric in a generalized
fashion (Section 4.2), enabling a resources discovery process
for finding a suitable host for each heterogeneous resource requested
by cloud customers (Section 4.1).

To generalize these hardware types, specialized hardware data-
sheets have been investigated and key (model, architecture and
manufacture independent) properties associated to each accelerator
have been extracted. Thus, GPUs are characterized by the sub-
classes of the GPUNonFunctionalProperties class: the GPUCom-
putingProperty subclass identifies properties of GPU processors
such as the clock frequency, Flops at single and double precision,
and numbers of streams; and the GPPMemoryProperty subclass
is used to describe the memory system of GPUs, in which memory
bandwidth and memory size are included as subclasses.

The subclasses of the MICNonFunctionalProperty class are
used to characterize MIC accelerators. The MICserieProperty subclass
includes XeonPhi3110, XeonPhi5120, XeonPhi7110, Xeon-
Phi7120 individuals; the MICComputing subclass describes
compute capabilities of MIC hardware, such as architecture, number
of cores, and frequency of the cores; and the MICMemory subclass
allows to describe memory cache size, memory type, memory size,
and memory controller features into its subclasses.

The subclasses of the FPGANonFunctionalProperties class are
used to categorize FGAs: the FPGAarchitecture subclass with Ar-
ria, Cyclone, MAX, Stratix, and Virtex individuals; the FPGAGen-
eration subclass distinguishes between possible incompatibilities
arising between FPGAs generations; the FPGARoutingArchitec-
ture subclass with HFPGA, HRSA, and APEX routing schemes de-
scribe different configurations of FPGAs; the FPGAClock subclass
identifies properties related to the maximum frequency and number
of clocks described by its nested subclasses; the FGAComput-
ingBlock subclass contains the FGAComputingBlockDSP subclass
to describe DSPs architecture and the number of DSPs in-
TEGRATED in the FPGA, and the FGAComputingLogicBlocks subclass
to identify connection type, number of lookup tables, and
number of flip-flops available in the computing block properties
class; I/O specifications of the accelerator are described in the
FPGA0Block subclass, and this is composed of the FPGA0-
NumberI0Blocks, and FPGA0RoutingChannels classes, describing the

![Fig. 2. Top level classes of CL-Ontology.](image-url)
number of horizontal and vertical routing channels; finally, the FPGAIOBlockConnectionBox subclass identifies communication specifications of FPGAs, such as connection type, with bidirectional and unidirectional elements as individuals, number of connections per box, and number of connection boxes.

3.2.2. The Functional Properties class

The FunctionalProperties class has been extended from the mOSAIC ontology to include multiple resource abstraction methods. Thus, this class consists of: Accounting, BackupAndRecovery, Consistency, Encryption, Identification, Replication, Monitoring, Management, and ResourceAbstractionDescription subclasses.

Fig. 4 depicts the physical classes of FunctionalProperties. The Monitoring subclass was extended with physical and resource abstractions monitoring processes. Previously, in the mOSAIC ontology, this subclass focused only on resources offered to the customers. Two subclasses have been added: the AbstractedResourceMonitoring subclass, identifying metrics associated with heterogeneous resource abstraction methods offered by vendors, and the PhysicalResourceMonitoring subclass, to describe metrics of physical resources. The metrics associated to the AbstractedResourceMonitoring subclass are composed of: BandwidthUsage in which DownloadUsage and UploadUsage are subclasses; StorageUsage; MemoryUsage in with GeneralMemoryUsage and SpecificHardwareMemoryUsage are subclasses to provide metrics on the memory of heterogeneous systems; and, in the same manner, the ProcessingUsage class provides metrics on the CPUProcessingUsage subclass and the SpecificHardwareProcessingUsage subclass. In addition to the metrics described in the subclasses for the AbstractedResourceMonitoring class, the PowerConsumption class was included as subclass into the PhysicalResourceMonitoring class to describe the monitoring process of the energy consumed by physical resources.

The VMDescription class has been replaced with a ResourceAbstractionDescription class, to capture properties associated with containers and dedicated servers, currently offered as resource abstraction methods by cloud vendors.

The last FunctionalProperties subclass modified to incorporate heterogeneity in cloud environments is the Management class. The mOSAIC ontology associated subclasses are: ImageManagement, NetworkManagement, StorageManagement. In addition to these, the InfrastructureMonitoringManagement subclass has been incorporated into the CL-Ontology to specify management frameworks for collecting metrics from heterogeneous hardware, including as individuals: OpenStackCeilometer, AmazonCloudWatch, AppDynamics, and SNAP. The ServicesManagement subclass has added to the Management class for supporting service oriented architectures, in which services configurations and properties are specified by users but managed by vendors. A group of individuals has been added to the Management class, currently used in Public and Private Clouds, such as OpenStack, AWSElasticBeans, Mesos, Slurm, AWSCloudformation, and Rocks individuals.

3.3. The Layer class

The Layer class, Fig. 5, is defined based on OCCI, NIST, and IBM Cloud Computing Reference Architecture to identify firmware, hardware, and software of the Cloud. New subclasses have been incorporated into the Application, FirmwareAndSoftware, OperationalLayer, ServiceLayer, and SoftwareKernel classes. The Application class describing services defined by users by using the UserComponents subclass, does not support current service oriented architectures where users define their applications using a Service Description Language (SDL) in which components and topology are defined as part of the specification of services. To support users applications and requests based on SOAs, the SequencingComponent subclass has been added to the Application class, describing communications between user components. This supports OpenStack Solum [46] and Apache Brooklyn [47] as individuals, enabling service oriented architectures in PaaS services; and the OpenStack Heat [48] individual representing service oriented architectures orchestration in IaaS services.

The FirmwareAndHardware class describes the firmware and hardware of cloud infrastructures. The Hardware subclass, the classes representing physical resources Cache, CPU and Memory; have been nested into the CommodityHardware class, where traditional cloud hardware is included. In addition, Network has been incorporated as a subclass of CommodityHardware to describe available network connections between physical hardware with Ethernet, FastEthernet, GigabitEthernet and 10GbEthernet subclasses to incorporate IEEE-802.3 — 10 Mbps, IEEE-802.3u — 100 Mbps, IEEE-802.3z — 1000 Mbps, and IEEE-802.3ae — 10 Gbps protocols. Moreover, to decouple specialized hardware from commodity hardware, the SpecificHardware subclass with Coprocessor and SpecializedNetwork children have been added to the Hardware class. The Coprocessor class contains FPGA, GPU and DFE subclasses to define specific hardware accelerators that can be attached to the Cloud, while the SpecializedNetwork class is
Fig. 4. Functional properties of CL-Ontology.

Fig. 5. Layer class of CL-Ontology.

included with **100GbEthernet** as a subclass to describe the IEEE-802.3bj protocol and Infiniband connections. However, as specific services might require specialized libraries only supported by concrete hardware, an object property **requiresLibrary** has been added to describe this relationship between the **Coprocessor** and **Library** classes.

The **OperationalLayer** class was incorporated into the mOSAiC ontology based on the IBM Cloud Computing Reference Architecture to describe the operational infrastructure layer of cloud computing systems. However, it does not contain nested classes as the mOSAiC ontology focuses on interoperability in the Cloud from the user’s perspective. To describe the different resource managers that can be currently deployed in Cloud systems, the **BaremetalResourceManager**, **ContainerResourceManager**, and **VMResourceManager** classes have been incorporated into this class, having as individuals: **OpenStack**, **Mesos**, **ROCKS**, and **SLURM**; and with the object properties: **offersVirtualMachines** in the **VMResourceManager** domain, **offersContainers** in **ContainerResourceManager** domain, and **offersDedicatedServers** in **BaremetalResourceManager** domain.

In the mOSAiC ontology, the **VirtualMachine** class was nested within the **ServiceLayer** class. The CL-Ontology moves this class into the **ResourceAbstraction** class, which is placed as a subclass of the **ServiceLayer** class together with the **DedicatedServer** and **DockerContainer** subclasses. The **ResourceAbstraction** class describes current resource abstraction methods in the cloud being used for deploying user applications – containers, virtual machines, and dedicated servers – these are a main cause of Cloud management fragmentation. All classes and subclasses using containerization techniques has been named with the prefix **Docker**, to differentiate them from mOSAiC ontology concept of “CloudletContainers”, used as entities to negotiate user SLAs with the “Cloud Negotiator” and “Cloud Mediator”.

The **SoftwareKernel** class describes the software internals of servers that virtualize resources offered to users. The **Hypervisor**, **Middleware**, **Monitor**, and **OperatingSystem** subclasses have been extended with the **DockersEngine** subclass to describe a software kernel supporting containers, instead of traditional virtual machines supported by the **Hypervisor** class. Moreover, the **ResourceManagerClient** subclass has been added to the **SoftwareKernel** class to describe the software clients installed in compute and storage servers and used by resource managers to govern resources. The **Monitor** class has been extended to represent a broader concept of monitoring resources with the **ResourceAbstractionMonitor** subclass being a modification of the **VirtualMachineMonitor** class of the mOSAiC ontology and representing the monitoring of resources abstractions. The **PhysicalResourcesMonitor** subclass has been added to support the monitoring of physical hardware resources.

Fig. 5 depicts new individuals incorporated into the CL-Ontology: **Hyper-V** and **Citrix** into the **Hypervisor** class, **Mesos** into the
Fig. 6. Components class and subclasses in CL-Ontology.

DockersEngine class; and OpenStackClient, MesosClient, OpenNebulaClient, RocksClient, and SlurmClient into the ResourceManagerClient class.

The Technology class, has been extended with the ResourceAbstractionMethods class. The VirtualizationTechnology class has been nested into this class. In addition, the DockerTechnology class has been incorporated to support containerization technologies, and the BareMetalTechnology class is used to represent direct access to dedicated resources without the use of virtualization/containerization techniques. The object properties have been completed with the addition of the hasAbstractionMethod property, and nested subproperties: hasDockerTechnology and hasBaremetalTechnology, with the hasVirtualizationTechnology class, being reused from the mOSAIC ontology.

3.4. The Component, Runtime and Stateless classes

The Component class is the main class of the CL-Ontology and it contains all the cloud elements. Foremost among these are resources, services, and elements of the infrastructure. Fig. 6 depicts the subclasses of the Component class. These are the Infrastructure subclass, the Environment subclass, the Resources subclass, the Tool subclass, the StatefullComponent subclass, the StatelessComponent subclass, the RuntimeComponent subclass, and the ProgrammingComponent subclass.

Most of classes and subclasses contained in the Component are subclasses of other classes described above. For brevity, only the modified classes and those appended to the mOSAIC ontology are described.

The RuntimeComponent class, Fig. 7(a), contains software elements performing management, selection, and evaluation tasks in cloud environments. The ResourceIncorporationEvaluator subclass is nested within the Evaluator subclass of the RuntimeComponent class and describes resources incorporated into the cloud resource fabric. The ResourceSelector class describes the selection of possible implementations and resource abstraction methods associated with users requests. The Manager subclass contains the ResourceIncorporationManager subclass, describing the actions performed in incorporating a newly added resource into the cloud fabric, the ResourceDiscoveryManager subclass describes the selection of resources that is used for deploying a service, and the ResourceDeploymentManager class describes the management of composition of services in a unified manner and it describes communicating single deployments of each service to the LocalResourceManager subclass, in which individuals are OpenStack, Kubernetes, and Marathon.

The Stateless class is depicted in Fig. 7(b). It describes elements of the services that do not have persistent state. It is contained within the Interfaces subclass and the Services subclass. The AdminServices subclass has been extended from the mOSAIC ontology to incorporate resource abstraction methods and resources deployment process support. Therefore, the AbstractedResourceMonitoring class, described above as it is also a subclass of FunctionalProperties, replaces the ResourceMonitoring class. Moreover, the ResourceDeployment class describes the actions for deploying resource abstractions in physical resources. It represents the interests of cloud providers who express their objectives in a resource deployment policy manner — e.g., improving the energy consumed by servers, or maximizing servers utilization, a DeploymentPolicy class and a GlobalGoal class have been incorporated into the ontology, representing efficiency objectives of providers, both are subclasses of the ResourceDeployment class.
Finally, the Statefull class in which the modifications over the mOSAIc ontology have been described in this section within the Layer, FirmwareAndHardware, and OperationalLayer classes, as Statefull subclasses are also subclasses supporting these entities.

4. Proposed architecture

A Service Oriented Architecture (SOA) allow end users to describe their cloud applications as service delivery work-flows descriptions or blueprints. These blueprints are compositions of functional components, associated resources, configurations, and sequencing constraints of those components. SOAs are suggestive of an organization in which components assume control over specific roles in an effort to isolate the cloud customer from the internal functioning of the Cloud and to recognize the benefits of allowing the cloud provider to have full control over their resources, a separation of concerns detailing how customers can focus on application life cycle management while allowing cloud providers to focus on the underlying resource life cycle management would create opportunities for significant optimizations in both domains. Example frameworks employing the SOA philosophy include OpenStack Solum [46] and Apache Brooklyn [47] in PaaS environments, and OpenStack Heat [48] in IaaS environments, however, none of these offer the separation of concerns as expressed above.

The architecture proposed in this paper is an SOA, introducing separation of concerns [49] as described above. This separation augments the traditional service oriented architectures by allowing users to concentrate on describing functional components, configurations, and service level agreement constraints and by allowing the cloud provider to concentrate on providing the appropriate resources to satisfy those requirements. In a cloud environment consisting of an heterogeneous resource fabric, there may be many different types of resource that fulfill the user's requirements. In that situation, the separation of concerns principle would allow the cloud service provider to make a final choice, and in doing so to optimize efficiency objectives such as improving resource utilization and reducing energy consumption.

Fig. 8 depicts a heterogeneous cloud infrastructure where the cloud management domains are separated into logical partitions each of which is in principle managed by dedicated resource manager. In practice these domains may be created dynamically by a Resource Coordinator as novel hardware types are incorporated into the resource fabric. The Resource Coordinator consists on several functional blocks that can be deployed as agents or services, several information storage components, and a Semantic Engine. This engine is the interface between the Cloud and its users, and the Cloud and candidate resources applying for incorporation into the resource fabric.

4.1. Resource coordinator service delivery work flow

The Resource Selection component of the Semantic Engine receives blueprints submitted by users (Label (1) in Fig. 8). Next to receive a blueprint, the Resource Selection component analyses the blueprint using the CL-Ontology. In this process, the Service Catalog is queried to obtain information on available implementations associated with the services requested by the blueprint. The Service Catalog stores available implementations offered by the cloud provider, supported by diverse resource abstractions on the heterogeneous hardware. For example, a matrix multiplication service may be recorded in the catalog as having implementations based on diverse physical and abstracted resources such as CPU, GPU, FPGA, containers and virtual machines.

The Resource Selection component uses the list of possible implementations and consults the CL-Ontology to construct a semantic-based resource blueprint, exploiting the semantic and syntactic structure of the CL-Ontology. This is forwarded to the Resource Discovery component (Label (2) in Fig. 8).

The URDs Storage contains a description of all resources that are part of the infrastructure, such as endpoints for deploying and monitoring resources, available abstraction methods, and managers information.

The Resource Discovery selects a hardware type and abstraction method associated with an existing resource in the cloud infrastructure. Accessing the URDs Storage, the Resource Discovery component retrieve information on concrete resources and technologies to support each service described in the resource blueprint. This information, and metrics provided by monitoring frameworks deployed in the infrastructure, act as inputs to heuristics that decide the efficiency objectives defined by providers.

As a result of this process, a specific implementation is chosen and captured in a resource blueprint specification, embodying resources in a particular logical partition of the Cloud. If no appropriate resource is found, the request is rejected and this outcome is communicated to the end user. Alternatively, if an appropriate resource is found, the Resource Deployment component (Label (3) in Fig. 8) interfaces with the appropriate logical partition via its logical resource manager to deploy the service as per user requirements.

4.2. Incorporating heterogeneous resources into the resource fabric

The process of incorporating heterogeneous resources into the cloud management domain is transparently executed using a Plug & Play mechanism [50]. The Resource Incorporation plugin (RI-plugin) deployed on each resource registers/deregisters the physical hardware with the Resource Coordinator. The information collected for registering a resource includes a description of the physical features, a mechanism for accessing the resource, a framework description associated with the management of the resource, and a telemetry endpoint with which the resource is registered and from which utilization information can be retrieved. As part of the registration process, the Semantic Engine receives the resource description and from it a semantic-based Unified Resource Description (URD) is created, referencing the semantic and syntactic structure of the CL-Ontology. The URD enables the management of multiple heterogeneous resources in a unified manner. URDs can thus describe bare metal, virtual machines, containers, networked hardware being treated as a group to preserve connectivity information, and software resource managers, hiding locally managed subsystems. Servers with attached accelerators such as GPUs, MICs and DFEs typically cannot be virtualized due to the specific nature of the accelerators. To incorporate these resources into the Cloud, these server–accelerator pairs can also be represented as a URDs. In some cases, it may be possible to virtualize the server and to associate a partition of its accelerator with that virtualized component. In that case, the virtual component and the accelerator partition are seen as a single URD. The granularity of an URD is thus dependent on what aspect of the resource is being exposed to the cloud.

Finally, as result, the URD is stored into the URDs Storage and, in this manner, can be accessed from Resource Discovery component to schedule deployments and, therefore, from Resource Deployment component to deploy services.

5. CloudLightning – realization of proposed architecture

The CloudLightning (CL) project is based on the principles of self-organization and self-management (SOSM). It addresses the complexity introduced by heterogeneous resources in large scale cloud computing infrastructures. Fig. 9 depicts the high level
overview of the components that build the CloudLightning architecture and the interactions between users and the system.

The CL project focuses on: (1) creating a heterogeneous cloud by exploring how specialized hardware, including high-performance computing machines, can be seamlessly integrated into the cloud resource fabric; (2) creating an SOA augmented with a separation of concerns approach to application and resource management; (3) moving the resource abstraction selection to the management of the cloud, allowing cloud providers to incorporate efficiency objectives on the resource fabric; and (4) addressing interoperability problems arising from using multiple heterogeneous resource managers at scale.

The CL system consists of a number of self-contained, loosely-coupled components.

- The Gateway Server component processes user requests in the form of blueprints. Each request is decomposed in multiple services and given to the Self Organising Self Management system (SOSM). Appropriate resources are located in infrastructure, the Gateway server then deploys services of the blueprint on to those resources using the deployment manifest associated with each service.

- The SOSM system component to interact with multiple resource management domains to identify appropriate resources that satisfy service level agreements and the efficiency objectives of the CSP.

- The CL-Plug and Play component to dynamically incorporate, remove, and configure new hardware resources and resource managers, existing or envisaged — including sub-systems, such as HPC systems.

- A Telemetry component to interface with multiple telemetry endpoints and provides a uniform interface between those end points and SOSM system.

Fig. 10 shows detailed view of the CL architecture as realization of the proposed architecture depicted in Fig. 8. On the left hand side, two interaction points with the CL system are shown: a new resource incorporation process into the cloud resource fabric, and the arrival of a blueprint.

When a Resource Incorporation (RI) plugin attempts to register a resource with the Cloud, the Plug and Play Server (PnP server). The role of the resource incorporation in the CloudLightning system is performed by the Plug and Play Server (PnP server), and it behaves at it is described in Section 4.
Therefore, each request received for registering/deregistering resources with the SOSM system is analyzed in the context of the CL-Ontology component, which checks the correctness of each request. Afterwards, a semantic-based CL-Resource (corresponding to URD in Fig. 8) is created in which the most significant information of the resource is represented, providing access to the physical resource via a unique identifier. The newly created CL-Resource is stored in a CL-Resource Storage (URDs Storage in Fig. 8), which is realized CL system by using a mongDB database for high availability. This database holds information on the resources which can be used by the SOSM when processing resource requests to satisfy blueprint descriptions.

Users requests, in the formal blueprints (Label 1 at Fig. 10), are processed by the Gateway Server component. There, requests are decomposed and, depending on the services required by the blueprint and on the available implementations for each service within the services catalog, appropriate resources are identified and recorded in a blueprint. These are forwarded to the SOSM system, specifically to the Cell Manager (Label 2 at Fig. 10).

The internal structure of the SOSM system acts as the Resource Discovery component as described in Fig. 8. Its hierarchical structure orchestrates multiple user requests targeting properly at the underlying logic partitions. The Cell Manager component, on top of the SOSM hierarchy, implements the semantic engine functionality provided by the Resource Selection component in Fig. 8. By using the CL-Ontology, semantic-based services requests are issued which result in a resourced blueprint. In such a blueprint, the identity of specific physical resources and resource abstractions are recorded and into which the appropriate service implementation will subsequently be deployed.

Requests are sent from the Cell Manager to one of the pRouters identifying the logical partition of the Cloud in which establish heterogeneous resources resides. pSwitches, situated under the pRouters, further partition the resource space into smaller and more efficiently manage domains. The lowest logical level in the SOSM hierarchy is occupied by virtual Rack Managers (vRMs). These resource managers directly control and, where appropriate, virtualize a subset of the physical resource fabric whose hardware type is reflected in on the type of is parent pRouter. While navigating through the SOSM hierarchy, resource requests are directed along a path which automatically results in them being satisfied by the “most suitable” underlying physical resource. This suitability is determined by the upward propagation of the status of the physical resources and associated metrics are combined, in each level of the hierarchy, into a measure known as Suitability Index (SI) [51]. In effect, requests follow the path determined by the highest value of the SI at each level in the hierarchy. Moreover, the efficiency objectives of the cloud provider can be captured as a vector of weights that is propagated downwards through the hierarchy, becomes part of the SI calculation and thus is used bias the resource selection, reflecting the relative importance dynamically placed by the provider on each objective.

The process of deploying multiple resource abstraction methods — virtual machines and containers and of having them cooperate, would require different resource managers to collaborate to deliver a composition of service hosted across these different resource types. From the users perspective, all services supported by heterogeneous resources should interact seamlessly as if they were in the same resource pool. Therefore, an integration strategy is used in CloudLightning to create a unified virtual network infrastructure management across all platforms horizontally [52]. OpenStack Neutron is used to connect physical resources to the same networking infrastructure but each is managed by an appropriate, and possibly distinct, resource manager.

When a service component resource blueprint is received at the vRM level, a resource abstraction method is initialized in order to support it. As result, associated to each service described in the original blueprint, an homologous service is created in a resourced template filled with resource abstraction type, endpoint, accessing method, and implementation chosen.

Once the resourced template is adequately filled with the information required to access the resource abstractions, it is returned to the Gateway Server (label 4 at Fig. 10), where information contained is used for deploying implementations associated to services [53] (label 5 at Fig. 10). By implementing this functionality, the Gateway Server realizes the Resource Deployment component described in the proposed architecture.

Finally, the control of the application is given back from the Gateway Server to the end user.

6. Conclusions and future work

This work was motivated by the desire to simplify the deployment of collaborating services across heterogeneous resources in a manner that automated resource interoperability. Prior to this work, expert users were required to manually configure collaborative environments. By creating a formal ontology capturing heterogeneity across resource abstraction methods, physical resources, and resource managers, it became possible to express HPC-like environments within the Cloud. This work is currently proposed as basis of the IEEE-2303, Standard for Adaptive Management of Cloud Computing Environments [54], with the hope of being supported and updated periodically.

The Ontology described in this work attempt to guide cloud architects in production of the next generation of cloud systems by:

- creating a central knowledge repository in which a common understanding of the information can be shared and improved.
- alleviating current interoperability and lock-in vendor issues between resource managers, resource abstractions, physical resources, and public and private cloud software stacks in inter/intra cloud environments.
- showing that to construct a system in which multiple heterogeneous resources can coexist in the same cloud environment is possible.
- proposing an ontology as part of a semantic engine to address the complexity of building HPC environments in Cloud.

In addition to the creation of the CL-Ontology, this paper proposes a conceptual architecture for supporting the processes of dynamic incorporation of hardware accelerators into the cloud resource fabric, and ontology-based resource management. An realization of this conceptual architecture is presented into the Cloud-Lightning system to illustrate how the CL-Ontology can be applied for autonomous resource management. Although this work is at an early stage of development, it has been used as an initial use case to illustrate the effectiveness of the semantic engine as an Ontology-based resource management for decision making processes.

Supporting dynamic expanding/contracting of resources into the cloud resource fabric, and increasing diversity in resource management/resource abstraction methods, focus future efforts on taking care of this aspects since the interaction points with the proposed architecture do not handle security and fault tolerance.
aspects. Therefore, additional work is needed to ensure an incremental design approach to incorporate to the CL-Ontology (1) fault tolerance in HPC in cloud environments; (2) security components and elements to avoid inadvertent requests or bogus resource incorporation actions that will result in corruption of the cloud information.

Finally, once the ontology-based resource management architecture will be integrated, future efforts will be placed on the evaluation of the performance, resources utilization, and energy consumption within the CloudLightning system, comparing the obtained results with other traditional resource management techniques.

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