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Project-Team STACK

Software Stack for Massively Geo-Distributed Infrastructures

IN COLLABORATION WITH: Laboratoire des Sciences du numerique de Nantes

RESEARCH CENTER
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THEME
Distributed Systems and middleware

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2. Overall Objectives

2.1. STACK in a Nutshell

The STACK team addresses challenges related to the management and advanced usages of Utility Computing infrastructures (i.e., Cloud, Fog, Edge, and beyond). More specifically, the team is interested in delivering appropriate system abstractions to operate and use massively geo-distributed ICT infrastructures, from the lowest (system) levels to the highest (application development) ones, and addressing crosscutting dimensions such as energy or security. These infrastructures are critical for the emergence of new kinds of applications related to the digitalization of the industry and the public sector (a.k.a. the Industrial and Tactile Internet).

2.2. Toward a STACK for Geo-Distributed Infrastructures

With the advent of Cloud Computing, modern applications have been developed on top of advanced software stacks composed of low-level system mechanisms, advanced middleware and software abstractions. While each of these layers has been designed to enable developers to efficiently use ICT resources without dealing with the burden of the underlying infrastructure aspects, the complexity of the resulting software stack has become a key challenge. As an example, Map/Reduce frameworks such as Hadoop have been developed to benefit from cpu/storage capacities of distinct servers. Running such frameworks on top of a virtualized cluster (*i.e.*, in a Cloud) can lead to critical situations if the resource management system decides to consolidate all the VMs on the same physical machine [101]. In other words, self-management decisions taken in isolation at one level (infrastructure, middleware, or application) may indirectly interfere with the decision taken by another layer, and globally affect the performance of the whole stack. Considering that geo-distributed ICT infrastructures significantly differ from the Cloud Computing ones regarding heterogeneity, resiliency, and the potential massive distribution of resources and networking environments [63], [96], we can expect that the complexity of the software stacks is going to increase. Such an assumption can be illustrated, for instance, by the sotfware architecture proposed in 2016 by the ETSI Mobile edge computing Industry Specification Group [88]. This architecture is structured around a new layer in charge of orchestrating distinct independent cloud systems, *a.k.a.* Virtual Infrastructure Managers (VIMs) in their terminology. By reusing VIMs, ETSI targets an edge computing resource management that behaves in the same fashion as Cloud Computing ones. While mitigating development requirements, such a proposal hides all management decisions that might be taken in the VIM of one particular site and thus may lead to conflicting decisions and consequently to non-desired states overall.

Through the STACK team, we propose to investigate the sotfware stack challenge as a whole. We claim it is the only way to limit as much as possible the complexity of the next generation software stack of geo-distributed ICT infrastructures. To reach our goal, we will identify major building blocks that should compose such a software stack, how they should be designed (*i.e.*, from the internal algorithms to the APIs they should expose), and finally how they should interact with each other.

Delivering such a software stack is an ambitious objective that goes beyond the activities of one research group. However, our expertise, our involvements in different consortiums (such as OpenStack) as well as our participation to different collaborative projects enable STACK members to contribute to this challenge in terms of architecture models, distributed system mechanisms and software artefacts, and finally, guideline reports on opportunities and constraints of geo-distributed ICT infrastructures.

3. Research Program

3.1. Overview

STACK research activities have been organized around four research topics. The two first ones are related to the resource management mechanisms and the programming support that are mandatory to operate and use ICT geo-distributed resources (compute, storage, network). They are transverse to the System/Middleware/Application layers, which generally composed a software stack, and nurture each other (*i.e.*, the resource management mechanisms will leverage abstractions/concepts proposed by the programming support axis and reciprocally). The third and fourth research topics are related to the Energy and Security dimensions (both also crosscutting the three software layers). Although they could have been merged with the two first axes, we identified them as independent research directions due to their critical aspects with respect to the societal challenges they represent. In the following, we detail the actions we plan to do in each research direction.

3.2. Resource Management

The challenge in this axis is to identify, design or revise mechanisms that are mandatory to operate and use a set of massively geo-distributed resources in an efficient manner [50]. This covers considering challenges at the scale of nodes, within one site (*i.e.*, one geographical location) and throughout the whole geo-distributed ICT infrastructure. It is noteworthy that the network community has been investigating similar challenges for the last few years [69]. To benefit from their expertise, in particular on how to deal with intermittent networks, STACK members have recently initiated exchanges and collaborative actions with some network research groups and telcos (see Sections 8.1 and 9.1). We emphasize, however, that we do not deliver contributions related to network equipments/protocols. The scientific and technical achievements we aim to deliver are related to the (distributed) system aspects.

3.2.1. Performance Characterization of Low-Level Building Blocks

Although Cloud Computing has enabled the consolidation of services and applications into a subset of servers, current operating system mechanisms do not provide appropriate abstractions to prevent (or at least control) the performance degradation that occurs when several workloads compete for the same resources [101]. Keeping in mind that server density is going to increase with physical machines composed of more and more cores and that applications will be more and more data intensive, it is mandatory to identify interferences that appear at a low level on each dimension (compute, memory, network, and storage) and propose countermeasures. In particular, previous studies [101], [61] on pros and cons of current technologies – virtual machines (VMs) [75], [83], containers and microservices – which are used to consolidate applications on the same server, should be extended: In addition to evaluating the performance we can expect from each of these technologies on a single node, it is important to investigate interferences that may result from cross-layer and remote communications [102]. We will consider in particular all interactions related to geo-distributed systems mechanisms/services that are mandatory to operate and use geo-distributed ICT infrastructures.

3.2.2. Geo-Distributed System Mechanisms

Although several studies have been highlighting the advantages of geo-distributed ICT infrastructures in various domains (see Section 3.), progress on how to operate and use such infrastructures is marginal. Current solutions [32] [33] are rather close to the initial Cisco Fog Computing proposal that only allows running domain-specific applications on edge resources and centralized Cloud platforms [40] (in other words, these solutions do not allow running stateful workloads in isolated environments such as containers or VMs). More recently, solutions leveraging the idea of federating VIMs (as the aforementioned ETSI MEC proposal [88]) have been proposed. ONAP [95], an industry-driven solution, enables the orchestration and automation of virtual network functions across distinct VIMs. From the academic side, FogBow [42] aims to support federations of Infrastructure-as-a-Service (IaaS) providers. Finally, NIST initiated a collaborative effort with IEEE to advance Federated Cloud platforms through the development of a conceptual architecture and a vocabulary[1]. Although all these projects provide valuable contributions, they face the aforementioned orchestration limitations (*i.e.*, they do not manage decisions taken in each VIM). Moreover, they all have been designed by only considering the developer/user's perspective. They provide abstractions to manage the life cycle of geo-distributed applications, but do not address administrative requirements.

[1] https://collaborate.nist.gov/twiki-cloud-computing/bin/view/CloudComputing/FederatedCloudPWGFC (Dec 2018).

To cope with specifics of Wide-Area networks while delivering most features that made Cloud Computing solutions successful also at the edge, our community should first identify limitations/drawbacks of current resource management system mechanisms with respect to the Fog/Edge requirements and propose revisions when needed [68], [81].

To achieve this aim, STACK members propose to conduct first a series of studies aiming at understanding the software architecture and footprint of major services that are mandatory for operating and using Fog/Edge infrastructures (storage backends, monitoring services, deployment/reconfiguration mechanisms, etc.). Leveraging these studies, we will investigate how these services should be deployed in order to deal with resources constraints, performance variability, and network split brains. We will rely on contributions that have been accomplished in distributed algorithms and self-* approach for the last decade. In the short and medium term, we plan to evaluate the relevance of NewSQL systems [53] to store internal states of distributed system mechanisms in an edge context, and extend our proposals on new storage backends such as key/value stores [52], [94], and burst buffers [103]. We also plan to conduct new investigations on data-stream frameworks for Fog and Edge infrastructures [47]. These initial contributions should enable us to identify general rules to deliver other advanced system mechanisms that will be mandatory at the higher levels in particular for the deployment and reconfiguration manager in charge of orchestrating all resources.

3.2.3. Capacity Planning and Placement Strategies

An objective shared by users and providers of ICT infrastructures is to limit as much as possible the operational costs while providing the expected and requested quality of service (QoS). To optimize this cost while meeting QoS requirements, data and applications have to be placed in the best possible way onto physical resources according to data sources, data types (stream, graphs), application constraints (real-time requirements) and objective functions. Furthermore, the placement of applications must evolve through time to cope with the fluctuations in terms of application resource needs as well as the physical events that occur at the infrastructure level (resource creation/removals, hardware failures, etc.). This placement problem, *a.k.a.* the deployment and reconfiguration challenge as it will be described in Section 3.3, can be modelized in many different ways, most of the time by multi-dimensional and multi-objective bin-packing problems or by scheduling problems which are known to be difficult to solve. Many studies have been performed, for example, to optimize the placement of virtual machines onto ICT infrastructures [77]. STACK will inherit the knowledge acquired through previous activities in this domain, particularly its use of constraint programming strategies in autonomic managers [73], [72], relying on MAPE (monitor, analyze, plan, and execute) control loops. While constraint programming approaches are known to hardly scale, they enable the composition of various constraints without requiring to change heuristic algorithms each time a new constraint has to be considered [71]. We believe it is a strong advantage to deal with the diversity brought by geo-distributed ICT infrastructures. Moreover, we have shown in previous work that decentralized approaches can tackle the scalability issue while delivering placement decisions good enough and sometimes close to the optimal [87].

Leveraging this expertise, we propose, first, to identify new constraints raised by massively geo-distributed infrastructures (*e.g.*, data locality, energy, security, reliability and the heterogeneity and mobility of the underlying infrastructure). Based on this preliminary study, we will explore new placement strategies not only for computation sandboxes but for data (location, replication, streams, etc.) in order to benefit from the geo-distribution of resources and meet the required QoS.These investigations should lead to collaborations with operational research and optimization groups such as TASC, another research group from IMT Atlantique.

Second, we will leverage contributions made on the previous axis “Performance Characterization of Low-Level Building Blocks” to determine how the deployment of the different units (software components and data sets) should be executed in order to reduce as much as possible the time to reconfigure the system (*i.e.*, the *Execution* phase in the control loop). In some recent work [83], we have shown that the provisioning of a new virtual machine should be done carefully to mitigate boot penalties. More generally, proposing an efficient action plan for the *Execution* phase will be a major point as Wide-Area-Network specifics may lead to significant delays, in particular when the amount of data to be manipulated is important.

Finally, we will investigate new approaches to decentralize the placement process while considering the geo-distributed context. Among the different challenges to address, we will study how a combination of autonomic managers, at both the infrastructure and application levels [60], could be proposed in a decentralized manner. Our first idea is to geo-distribute a fleet of small control loops over the whole infrastructure. By improving the locality of data collection and weakening combinatorics, these loops would allow the system to address responsiveness and quality expectations.

3.3. Programming Support

We pursue two main research directions relative to new programming support: first, developing new programming models with appropriate support in existing languages (libraries, embedded DSLs, etc.) and, second, providing new means for deployment and reconfiguration in geo-distributed ICT environments, principally supporting the mapping of software onto the infrastructure. For both directions two levels of challenges are considered. On the one hand, the *generic* level refers to efforts on programming support that can be applied to any kind of distributed software, application or system. On this level, contributions could thus be applied to any of the three layers addressed by STACK (*i.e.*, system, middleware or application). On the other hand, the corresponding generic programming means may not be appropriate in practice (*e.g.*, requirements for more dedicated support, performance constraints, etc.), even if they may lead to interesting general properties. For this reason, a *specific* level is also considered. This level could be based on the generic one but addresses specific cases or domains.

3.3.1. Programming Models and Languages Extensions

The current landscape of programming support for cloud applications is fragmented. This fragmentation is based on apparently different needs for various kinds of applications, in particular, web-based, computation-based, focusing on the organization of the computation, and data-based applications, within the last case a quite strong dichotomy between applications considering data as sets or relations, close to traditional database applications and applications considering data as real-time streams. This has led to various programming models, in a loose sense, including for instance microservices, graph processing, dataflows, streams, etc. These programming models have mostly been offered to the application programmer in the guise of frameworks, each offering subtle variants of the programming models with various implementation decisions favoring particular application and infrastructure settings. Whereas most frameworks are dedicated to a given programming model, *e.g.*, basic Pregel [82], Hive [97], Hadoop [98], some of them are more general-purpose through the provision of several programming models, *e.g.*, Flink [46] and Spark [79]. Finally, some dedicated language support has been considered for some models (*e.g.*, the language SPL underlying IBM Streams [74]) as well as core languages and calculi (*e.g.*, [43], [92]).

This situation raises a number of challenges on its own, related to a better structuring of the landscape. It is necessary to better understand the various programming models and their possible relations, with the aim of facilitating, if not their complete integration, at least their composition, at the conceptual level but also with respect to their implementations, as specific languages and frameworks.

Switching to massively geo-distributed infrastructures adds to these challenges by leading to a new range of applications (*e.g.*, smart-* applications) that, by nature, require mixing these various programming models, together with a much more dynamic management of their runtime.

In this context, STACK would like to explore two directions:

- First, we propose to contribute to generic programming models and languages to address composability of different programming models [55]. For example, providing a generic stream data processing model that can operate under both data stream [46] and operation stream [104] modes, thus streams can be processed in micro batches to favour high throughput or record by record to sustain low latency. Software engineering properties such as separation of concerns and composition should help address such challenges [35], [93]. They should also facilitate the software deployment and reconfiguration challenges discussed below.

- Second, we plan to revise relevant programming models, the associated specific languages, and their implementation according to the massive geo-distribution of the underlying infrastructure, the data sources, and application end-users. For example, although SPL is extensible and distributed, it has been designed to run on multi-cores and clusters [74]. It does not provide the level of dynamicity required by geo-distributed applications (*e.g.*, to handle topology changes, loss of connectivity at the edge, etc.). Moreover, as more network data transfers will happen within a massively geo-distributed infrastructure, correctness of data transfers should be guaranteed. This has potential impact from the programming models to their implementations.

3.3.2. Deployment and Reconfiguration Challenges

The second research direction deals with the complexity of deploying distributed software (whatever the layer, application, middleware or system) onto an underlying infrastructure. As both the deployed pieces of software and the infrastructures addressed by STACK are large, massively distributed, heterogeneous and highly dynamic, the deployment process cannot be handled manually by developers or administrators. Furthermore, and as already mentioned in Section 3.2, the initial deployment of some distributed software will evolve through time because of the dynamicity of both the deployed software and the underlying infrastructures. When considering reconfiguration, which encompasses deployment as a specific case, the problem becomes more difficult for two main reasons: (1) the current state of both the deployed software and the infrastructure has to be taken into account when deciding on a reconfiguration plan, (2) as the software is already running the reconfiguration should minimize disruption time, while avoiding inconsistencies [80], [85]. Many deployment tools have been proposed both in academia and industry [57]. For example, Ansible [2], Chef [3] and Puppet [4] are very well-known generic tools to automate the deployment process through a set of batch instructions organized in groups (*e.g.*, *playbooks* in Ansible). Some tools are specific to a given environment, like Kolla to deploy OpenStack, or the embedded deployment manager within Spark. Few reconfiguration capabilities are available in production tools such as *scaling* and *restart* after a fault [5] [6]. Academia has contributed to generic deployment and reconfiguration models. Most of these contributions are component-based. Component models divide a distributed software as a set of component instances (or modules) and their assembly, where components are connected through well defined interfaces [93]. Thus, modeling the reconfiguration process consists in describing the life cycle of different components and their interactions. Most component-based approaches offer a fixed life cycle, *i.e.*, identical for any component [62]. Two main contributions are able to customize life cycles, Fractal [45], [38] and its evolutions [35], [36], [59], and Aeolus [54]. In Fractal, the *control* part of a component (*e.g.*, its life cycle) is modeled itself as a component assembly that is highly flexible. Aeolus, on the other hand, offers a finer control on both the evolution and the synchronization of the deployment process by modeling each component life cycle with a finite state machine.

A reconfiguration raises at least five questions, all of them are correlated: (1) *why software has to be reconfigured?* (monitoring, modeling and analysis) (2) *what should be reconfigured?* (software modeling and analysis), (3) *how should it be reconfigured?* (software modeling and planning decisions), (4) *where should it be reconfigured?* (infrastructure modeling and planning decisions), and (5) *when to reconfigure it?* (scheduling algorithms). STACK will contribute to all aspects of a reconfiguration process as described above. However, according to the expertise of STACK members, we will focus mainly on the three first questions: *why*, *what* and *how*, leaving questions *where* and *when* to collaborations with operational research and optimization teams.

First of all, we would like to investigate *why software has to be reconfigured?* Many reasons could be mentioned, such as hardware or software fault tolerance, mobile users, dynamicity of software services, etc. All those reasons are related somehow to the Quality of Service (QoS) or the Service Level Agreement (SLA) between the user and the Cloud provider. We first would like to explore the specificities of QoS and SLAs

[2] https://www.ansible.com/
[3] https://www.chef.io/chef/
[4] https://puppet.com/
[5] https://kubernetes.io/
[6] https://jujucharms.com/

in the case of massively geo-distributed ICT environments [89]. By being able to formalize this question, analyzing the requirement of a reconfiguration will be facilitated.

Second, we think that four important properties should be enhanced when deploying and reconfiguring models in massively geo-distributed ICT environments. First, as low-latency applications and systems will be subject to deployment and reconfiguration, the performance and the ability to scale are important. Second, as many different kinds of deployments and reconfigurations will concurrently hold within the infrastructure, processes have to be reliable, which is facilitated by a fine-grained control of the process. Finally, as many different software elements will be subject to deployment and reconfiguration, common generic models and engines for deployment and reconfiguration should be designed [44]. For these reasons, we intend to go beyond Aeolus by: first, leveraging the expression of parallelism within the deployment process, which should lead to better performance; second, improving the separation of concerns between the component developer and the reconfiguration developer; third, enhancing the possibility to perform concurrent and decentralized reconfigurations.

Research challenges relative to programming support have been presented above. Many of these challenges are related, in different manners, to the resource management level of STACK or to crosscutting challenges, *i.e.*, energy and security. First, one can notice that any programming model or deployment and reconfiguration implementation should be based on mechanisms related to resource management challenges. For this reason, all challenges addressed within this section are linked with lower level building blocks presented in Section 3.2. Second, as detailed above, deployment and reconfiguration address at least five questions. The question *what?* is naturally related to programming support. However, questions *why*, *how?*, *where?* and *when?* are also related to Section 3.2, for example, to monitoring and capacity planning. Moreover, regarding the deployment and reconfiguration challenges, one can note that the same goals recursively happen when deploying the control building blocks themselves (bootstrap issue). This comforts the need to design generic deployment and reconfiguration models and frameworks. These low-level models should then be used as back-ends to higher-level solutions. Finally, as *energy* and *security* are crosscutting themes within the STACK project, many additional energy and security considerations could be added to the above challenges. For example, our deployment and reconfiguration frameworks and solutions could be used to guarantee the deployment of end-to-end security policies or to answer specific energy constraints [70] as detailed in the next section.

3.4. Energy

The overall electrical consumption of DCs grows according to the demand of Utility Computing. Considering that the latter has been continuously increasing since 2008, the energy footprint of Cloud services overall is nowadays critical with about 91 billion kilowatt-hours of electricity [91]. Besides the ecological impact, the energy consumption is a predominant criterion for providers since it determines a large part of the operational cost of their infrastructure. Among the different appraoches that have been investigated to reduce the energy footprint, some studies have been ingestigating the use of renewable energy sources to power microDCs [64]. Workload distribution for geo-distributed DCs is also another promising approach [66], [78], [99]. Our research will extend these results with the ultimate goal of considering the different opportunities to control the energy footprint across the whole stack (hardware and software opportunities, renewable energy, thermal management, etc.). In particular, we identified several challenges that we will address in this context within the STACK framework.

First, we propose to evaluate the energy efficiency of low-level building blocks, from the viewpoints of computation (VMs, containers, microkernel, microservices) [58] and data (hard drives, SSD, in-memory storage, distributed file systems). For computations, in the continuity of our previous work [56], [73], we will investigate workload placement policies according to energy (minimizing energy consumption, power capping, thermal load balancing, etc.). Regarding the data dimension, we will investigate, in particular, the trade-offs between energy consumption and data availability, durability and consistency [51], [94]. Our ambition is to propose an adaptive energy-aware data layout and replication scheme to ensure data availability with minimal energy consumption. It is noteworthy that these new activities will also consider our previous work on DCs partially powered by renewable energy (see the SeDuCe project, in Section 6.7), with the ultimate goal of reducing the CO_2 footprint.

Second, we will complete current studies to understand pros and cons of massively geo-distributed infrastructures from the energy perspective. Addressing the energy challenge is a complex task that involves considering several dimensions such as the energy consumption due to the physical resources (CPU, memory, disk, network), the performance of the applications (from the computation and data viewpoints), and the thermal dissipation caused by air conditioning in each DC. Each of these aspects can be influenced by each level of the software stack (*i.e.*, low-level building blocks, coordination and autonomous loops, and finally application life cycle). In previous projects, we have studied and modeled the consumption of the main components, notably the network, as part of a single microDC. We plan to extend these models to deal with geo-distribution. The objective is to propose models that will enable us to refine our placement algorithms as discussed in the next paragraph. These models should be able to consider the energy consumption induced by all WAN data exchanges, including site-to-site data movements as well as the end users' communications for accessing virtualized resources.

Third, we expect to implement green-energy-aware balancing strategies, leveraging the aforementioned contributions. Although the infrastructures we envision increase complexity (because WAN aspects should also be taken into account), the geo-distribution of resources brings several opportunities from the energy viewpoint. For instance, it is possible to define several workload/data placement policies according to renewable energy availability. Moreover, a tightly-coupled software stack allows users to benefit from such a widely distributed infrastructure in a transparent way while enabling administrators to balance resources in order to benefit from green energy sources when available. An important difficulty, compared to centralized infrastructures, is related to data sharing between software instances. In particular, we will study issues raised by the distribution and replication of services across several microDCs. In this new context, many challenges must be addressed: where to place the data (Cloud, Edge) in order to mitigate dat a movements? What is the impact in terms of energy consumption, network and response time of these two approaches? How to manage the consistency of replicated data/services? All these aspects must be studied and integrated into our placement algorithms.

Fourth, we will investigate the energy footprint of the current techniques that address failure and performance variability in large-scale systems. For instance, *stragglers* (*i.e.*, tasks that take a significantly longer time to finish than the normal execution time) are natural results of performance variability, they cause extra resource and energy consumption. Our goal is to understand the energy overhead of these techniques and introduce new handling techniques that take into consideration the energy efficiency of the platform [86].

Finally, in order to answer specific energy constraints, we want to reify energy aspects at the application level and propose a metric related to the use of energy (Green SLA [34]), for example to describe the maximum allowed CO_2 emissions of a Fog/Edge service. Unlike other approaches [67], [39], [65] that attempt to identify the best trade-off, we want to offer to developers/end-users the opportunity to select the best choice between application performance, correctness and energy footprint. Such a capability will require reifying the energy dimension at the level of big-data and interactive applications. Besides, with the emergence of renewable energy (*e.g.*, solar panels for microDC), investigating the energy consumption *vs* performance trade-off [70] and the smart usage of green energy for ICT geo-distributed services seems promising. For example, we want to offer the opportunity to developers/end-users to control the scaling of the applications based on this trade-off instead of current approaches that only considered application load. Providing such a capability will also require appropriate software abstractions.

3.5. Security

Because of its large size and complex software structure, geo-distributed applications and infrastructures are particularly exposed to security and privacy issues [90]. They are subject to numerous security vulnerabilities that are frequently exploited by malicious attackers in order to exfiltrate personal, institutional or corporate data. Securing these systems require security and privacy models and corresponding techniques that are applicable at all software layers in order to guard interactions at each level but also between levels. However, very few security models exist for the lower layers of the software stack and no model enables the handling of interactions involving the complete software stack. Any modification to its implementation, deployment status, configuration, etc., may introduce new or trigger existing security and privacy issues. Finally, applications that execute on top of the software stack may introduce security issues or be affected by vulnerabilities of the stack. Overall, security and privacy issues are therefore interdependent with all other activities of the STACK team and constitute an important research topic for the team.

As part of the STACK activities, we consider principally security and privacy issues related to the vertical and horizontal compositions of software components forming the software stack and the distributed applications running on top of it. Modifications to the *vertical composition* of the software stack affect different software levels at once. As an example, side-channel attacks often target virtualized services (*i.e.*, services running within VMs); attackers may exploit insecure hardware caches at the system level to exfiltrate data from computations at the higher level of VM services [84], [100]. Security and privacy issues also affect *horizontal compositions*, that is, compositions of software abstractions on one level: most frequently horizontal compositions are considered on the level of applications/services but they are also relevant on the system level or the middleware level, such as compositions involving encryption and database fragmentation services.

The STACK members aim at addressing two main research issues: enabling full-stack (vertical) security and per-layer (horizontal) security. Both of these challenges are particularly hard in the context of large geo-distributed systems because they are often executed on heterogeneous infrastructures and are part of different administrative domains and governed by heterogeneous security and privacy policies. For these reasons they typically lack centralized control, are frequently subject to high latency and are prone to failures.

Concretely, we will consider two classes of security and privacy issues in this context. First, on a general level, we strive for a method for the programming and reasoning about compositions of security and privacy mechanisms including, but not limited to, encryption, database fragmentation and watermarking techniques. Currently, no such general method exists, compositions have only been devised for specific and limited cases, for example, compositions that support the commutation of specific encryption and watermarking techniques [76], [48]. We provided preliminary results on such compositions [49] and have extended them to biomedical, notably genetic, analyses in the e-health domain [41]. Second, on the level of security and privacy properties, we will focus on isolation properties that can be guaranteed through vertical and horizontal composition techniques. We have proposed first results in this context in form of a compositional notion of distributed side channel attacks that operate on the system and middleware levels [37].

It is noteworthy that the STACK members do not have to be experts on the individual security and privacy mechanisms, such as watermarking and database fragmentation. We are, however, well-versed in their main properties so that we can integrate them into our composition model. We also interact closely with experts in these techniques and the corresponding application domains, notably e-health for instance, in the context of the PRIVGEN project[7], see Section 9.1.

More generally, we highlight that security issues in distributed systems are very closely related to the other STACK challenges, dimensions and research directions. Guaranteeing security properties across the software stack and throughout software layers in highly volatile and heterogeneous geo-distributed systems is expected to harness and contribute results to the self-management capabilities investigated as part of the team's resource management challenges. Furthermore, security and privacy properties are crosscutting concerns that are intimately related to the challenges of application life cycle management. Similarly, the security issues are also closely related to the team's work on programming support. This includes new means for programming, notably in terms of event and stream programming, but also the deployment and reconfiguration challenges, notably concerning automated deployment. As a crosscutting functionality, the security challenges introduced above must be met in an integrated fashion when designing, constructing, executing and adapting distributed applications as well as managing distributed resources.

4. Application Domains

[7] Privacy-preserving sharing and processing of genetic data, https://privgen.cominlabs.u-bretagneloire.fr/fr

4.1. Overview

Supporting industrial actors and open-source communities in building an advanced software management stack is a key element to favor the advent of new kinds of information systems as well as web applications. Augmented reality, telemedecine and e-health services, smart-city, smart-factory, smart-transportation and remote security applications are under investigations. Although, STACK does not intend to address directly the development of such applications, understanding their requirements is critical to identify how the next generation of ICT infrastructures should evolve and what are the appropriate software abstractions for operators, developers and end-users. STACK team members have been exchanging since 2015 with a number of industrial groups (notably Orange Labs and Airbus), a few medical institutes (public and private ones) and several telecommunication operators in order to identify both opportunities and challenges in each of these domains, described hereafter.

4.2. Industrial Internet

The Industrial Internet domain gathers applications related to the convergence between the physical and the virtual world. This convergence has been made possible by the development of small, lightweight and cheap sensors as well as complex industrial physical machines that can be connected to the Internet. It is expected to improve most processes of daily life and decision processes in all societal domains, affecting all corresponding actors, be they individuals and user groups, large companies, SMEs or public institutions. The corresponding applications cover: the improvement of business processes of companies and the management of institutions (*e.g.*, accounting, marketing, cloud manufacturingi, etc.); the development of large "smart" applications handling large amounts of geo-distributed data and a large set of resources (video analytics, augmented reality, etc.); the advent of future medical prevention and treatment techniques thanks to the intensive use of ICT systems, etc. We expect our contributions will favor the rise of efficient, correct and sustainable massively geo-distributed infrastructures that are mandatory to design and develop such applications.

4.3. Internet of Skills.

The Internet of Skills is an extension of the Industrial Internet to human activities. It can be seen as the ability to deliver physical experiences remotely (*i.e.*, via the Tactile Internet). Its main supporters advocate that it will revolutionize the way we teach, learn, and interact with pervasive resources. As most applications of the Internet of Skills are related to real time experiences, latency may be even more critical than for the Industrial Internet and raise the locality of computations and resources as a priority. In addition to identifying how Utility Computing infrastructures can cope with this requirement, it is important to determine how the quality of service of such applications should be defined and how latency and bandwidth constraints can be guaranteed at the infrastructure level.

4.4. e-Health

The e-Health domain constitutes an important societal application domain of the two previous areas. The STACK teams is investigating distribution, security and privacy issues in the fields of systems and personalized (aka. precision) medicine. The overall goal in these fields is the development of medication and treatment methods that are tailored towards small groups or even individual patients.

We are working, as part of the ongoing PrivGen CominLabs collaborative project on new means for the sharing of genetic data and applications in the Cloud. More generally, we are applying and developing corresponding techniques for the medical domains of genomics, immunobiology and transplantalogy in the international network SHLARC and the regional networks SysMics and Oncoshare: there, we investigate how to secure and preserve privacy if potentially sensitive personal data is moved and processed by distributed biomedical analyses.

We are also involved in the SyMeTRIC regional initiative where preliminary studies have been conducted in order to build a common System Medicine computing infrastructure to accelerate the discovery and validation of bio-markers in the fields of oncology, transplantation, and chronic cardiovascular diseases. The challenges were related to the need of being able to perform analyses on data that cannot be moved between distinct locations.

The STACK team will continue to contribute to the e-Health domain by harnessing advanced architectures, applications and infrastructures for the Fog/Edge.

4.5. Network Virtualization and Mobile Edge Services.

Telecom operators have been among the first to advocate the deployment of massively geo-distributed infrastructures, in particular through working groups such as Mobile Edge Computing at the European Telecommunication Standards Institute[8]. The initial reason is that geo-distributed infrastructures will enable Telecom operators to virtualize a large part of their resources and thus reduce capital and operational costs. As an example, we are investigating through the I/O Lab, the joint lab between Orange and Inria, how can a Centralized Radio Access Networks (*a.k.a.* C-RAN or Cloud-RAN) be supported for 5G networks. We highlight that our expertise is not on the network side but rather on where and how we can deploy, allocate and reconfigure software components, which are mandatory to operate a C-RAN infrastructure, in order to guarantee the quality of service expected by the end-users. Finally, working with actors from the network community is a valuable advantage for a distributed system research group such as STACK. Indeed, achievements made within one of the two communities serve the other.

5. Highlights of the Year

5.1. Highlights of the Year

Regarding scientific results, the team has produced a number of outstanding results on the management of resources and data in large-scale infrastructures, notably on how speeding up VM and Docker boot time by reducing the I/O operations [16], on how to place container images across edge servers in such a way that an image can be retrieved from any edge server fast and in a predictable time [14], and how the placement challenge of data and computations accross multiple sites can be addressed by using Constraint Programming techniques in a general manner [22].

We also deliver two other important contributions. In the first one, we propose an efficient graph partitioning method named Geo-Cut, which takes both the cost and performance objectives into consideration for large graph processing in geo-distributed DCs [8]. In the second one, we propose a model and a first implementation of a simulator to compare the energy footprint of different cloud architectures (single sites vs fully decentrlaized) [3].

On the software side, the team has pursued its efforts on the development of the EnosLib library and the resulting artifacts to help researchers perform experiment campaigns: https://discovery.gitlabpages.inria.fr/enoslib/theyuseit.html. We would like also to point it out the development of the field of dynamic reconfiguration of distributed software systems, in particular through the Concerto and Mad softwares: http://helene-coullon.fr/verdi/page/software/

On the platform side, the deployment of the SeDuCe testbed that allows researchers to investigate energy concerns in data-centers thanks to a numerous of energy sensors deployed across the dedicated facility is now fully operational: https://seduce.fr. Moreover, the team is still strongly involved in the different actions that aim to setup the SILECS platform.

[8] http://www.etsi.org/news-events/news/1078-2016-04-etsi-mobile-edge-computing-publishes-foundation-specifications.

5.1.1. Awards

In 2019, the team has received two individual award:

- **Outstanding Leadership Award** Shadi Ibrahim received an outstanding leadership award as program chair of the SmartData-2019 (http://cse.stfx.ca/~cybermatics/2019/smartdata/).
- **Best Tech Pitch** Hélène Coullon received the best tech pitch award at the IMT 5G event from a jury composed of both academic experts in 5G and experts from the Qualcomm company. Moreover, a grant has been awarded by France Brevet to Hélène Coullon to push further her efforts on Fog and Edge computing.

We would like also to highlight two other elements that underline the visibility and recognition of the team nationally and internationally. First, Thomas Ledoux became head of the teaching chair "ArchOps : architecture, déploiement et administration des infrastructures IT agiles" supported by Bodet Software. The ArchOps chair aims to develop skills in the design of distributed software architectures for engineering students at IMT Atlantique. Second, Shadi Ibrahim and Hélène Coullon, two members of the team, act as program track chairs of 20th IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing (CCGrid 2020), a major conference in the area of distributed systems.

6. New Software and Platforms

6.1. MAD

Madeus Application Deployer

KEYWORDS: Automatic deployment - Distributed Software - Component models - Cloud computing

SCIENTIFIC DESCRIPTION: MAD is a Python implementation of the Madeus deployment model for multi-component distributed software. Precisely, it allows to: 1. describe the deployment process and the dependencies of distributed software components in accordance with the Madeus model, 2. describe an assembly of components, resulting in a functional distributed software, 3. automatically deploy the component assembly of distributed software following the operational semantics of Madeus.

RELEASE FUNCTIONAL DESCRIPTION: Initial submission with basic functionalities of MAD

NEWS OF THE YEAR: Operational prototype.

- Participants: Christian Pérez, Dimitri Pertin, Hélène Coullon and Maverick Chardet
- Partners: IMT Atlantique - LS2N - LIP
- Contact: Hélène Coullon
- Publications: Madeus: A formal deployment model - Behavioral interfaces for reconfiguration of component models

6.2. Nitro

KEYWORDS: Cloud storage - Virtual Machine Image - Geo-distribution

SCIENTIFIC DESCRIPTION: Nitro is a storage system that is designed to work in geo-distributed cloud environments (i.e., over WAN) to efficiently manage Virtual Machine Images (VMIs).

Nitro employs fixed-size deduplication to store VMIs. This technique contributes to minimizing the network cost. Also, Nitro incorporates a network-aware scheduling algorithm (based on max flow algorithm) to determine which chunks should be pulled from which site in order to reconstruct the corresponding image on the destination site, with minimal (provisioning) time.

FUNCTIONAL DESCRIPTION: Geo-distributed Storage System to optimize Images (VM, containers, ...) management, in terms of cost and time, in geographically distributed cloud environment (i.e. data centers are connected over WAN).

- Authors: Jad Darrous, Shadi Ibrahim and Christian Pérez
- Contact: Shadi Ibrahim
- URL: https://gitlab.inria.fr/jdarrous/nitro

6.3. VMPlaces

KEYWORDS: Simulation - Virtualization - Scheduling

FUNCTIONAL DESCRIPTION: VMPlaces is a dedicated framework to evaluate and compare VM placement algorithms. This framework is composed of two major components: the injector and the VM placement algorithm. The injector is the generic part of the framework (i.e. the one you can directly use) while the VM placement algorithm is the part you want to study (or compare with available algorithms). Currently, the VMPlaceS is released with three algorithms:

Entropy, a centralized approach using a constraint programming approach to solve the placement/reconfiguration VM problem

Snooze, a hierarchical approach where each manager of a group invokes Entropy to solve the placement/reconfiguration VM problem. Note that in the original implementation of Snooze, it is using a specific heuristic to solve the placement/reconfiguration VM problem. As the sake of simplicity, we have simply reused the entropy scheduling code.

DVMS, a distributed approach that dynamically partitions the system and invokes Entropy on each partition.

- Participants: Adrien Lèbre, Jonathan Pastor and Mario Südholt
- Contact: Adrien Lèbre
- URL: http://beyondtheclouds.github.io/VMPlaceS/

6.4. ENOS

Experimental eNvironment for OpenStack

KEYWORDS: OpenStack - Experimentation - Reproducibility

FUNCTIONAL DESCRIPTION: Enos workflow :

A typical experiment using Enos is the sequence of several phases:

- enos up : Enos will read the configuration file, get machines from the resource provider and will prepare the next phase - enos os : Enos will deploy OpenStack on the machines. This phase rely highly on Kolla deployment. - enos init-os : Enos will bootstrap the OpenStack installation (default quotas, security rules, ...) - enos bench : Enos will run a list of benchmarks. Enos support Rally and Shaker benchmarks. - enos backup : Enos will backup metrics gathered, logs and configuration files from the experiment.

- Partner: Orange Labs
- Contact: Adrien Lèbre
- URL: http://enos.readthedocs.io/en/stable/

6.5. EnOSlib

EnOSlib is a library to help you with your experiments

KEYWORDS: Distributed Applications - Distributed systems - Evaluation - Grid Computing - Cloud computing - Experimentation - Reproducibility - Linux - Virtualization

FUNCTIONAL DESCRIPTION: EnOSlib is a library to help you with your distributed application experiments. The main parts of your experiment logic is made reusable by the following EnOSlib building blocks:

- Reusable infrastructure configuration: The provider abstraction allows you to run your experiment on different environments (locally with Vagrant, Grid'5000, Chameleon and more) - Reusable software provisioning: In order to configure your nodes, EnOSlib exposes different APIs with different level of expressivity - Reusable experiment facilities: Tasks help you to organize your experimentation workflow.

EnOSlib is designed for experimentation purpose: benchmark in a controlled environment, academic validation . . .

- Contact: Matthieu Simonin
- Publications: Toward a Holistic Framework for Conducting Scientific Evaluations of OpenStack - EnosStack: A LAMP-like stack for the experimenter
- URL: https://discovery.gitlabpages.inria.fr/enoslib/

6.6. Concerto

KEYWORDS: Reconfiguration - Distributed Software - Component models - Dynamic software architecture

FUNCTIONAL DESCRIPTION: Concerto is an implementation of the formal model Concerto written in Python. Concerto aloows to : 1. describe the life-cycle and the dependencies of software components, 2. describe a components assembly that forms the overall life-cycle of a distributed software, 3. automatically reconfigure a Concerto assembly of components by using a set of reconfiguration instructions as well as a formal operational semantics.

- Partners: IMT Atlantique - LS2N - LIP
- Contact: Maverick Chardet
- URL: https://gitlab.inria.fr/VeRDi-project/concerto

6.7. Platforms

6.7.1. OpenStack

OpenStack is the de facto open-source management system to operate and use Cloud Computing infrastructures. Started in 2012, the OpenStack foundation gathers 500 organizations including groups such as Intel, AT&T, RedHat, etc. The software platform relies on tens of services with a 6-month development cycle. It is composed of more than 2 millions of lines of code, mainly in Python, just for the core services. While these aspects make the whole ecosystem quite swift, they are also good signs of maturity of this community. We created and animated between 2016 and 2018 the Fog/Edge/Massively Distributed (FEMDC) Special Interest Group[9] and have been contributing to the Performance working group since 2015. The former investigates how OpenStack can address Fog/Edge Computing use cases whereas the latter addresses scalability, reactivity and high-availability challenges. In addition to releasing white papers and guidelines [96], the major result from the academic view point is the aforementioned EnOS solution, a holistic framework to conduct performance evaluations of OpenStack (control and data plane). In May 2018, the FEMDC SiG turned into a larger group under the control of the OpenStack foundation. This group gathers large companies such as Verizon, ATT, etc.

6.7.2. Grid'5000

Grid'5000 is a large-scale and versatile testbed for experiment-driven research in all areas of computer science, with a focus on parallel and distributed computing including Cloud, HPC and Big Data. It provides access to a large amount of resources: 12000 cores, 800 compute-nodes grouped in homogeneous clusters, and featuring various technologies (GPU, SSD, NVMe, 10G and 25G Ethernet, Infiniband, Omni-Path) and advanced monitoring and measurement features for traces collection of networking and power consumption, providing a deep understanding of experiments. It is highly reconfigurable and controllable. Researchers can

[9] https://wiki.openstack.org/wiki/Fog_Edge_Massively_Distributed_Clouds

experiment with a fully customized software stack thanks to bare-metal deployment features, and can isolate their experiment at the networking layer advanced monitoring and measurement features for traces collection of networking and power consumption, providing a deep understanding of experiments designed to support Open Science and reproducible research, with full traceability of infrastructure and software changes on the testbed. STACK members are strongly involved into the management and the supervision of the testbed, notably through the steering committee or the SeDuCe testbed described hereafter.

6.7.3. SeDuCe

The SeDuCe Project aims to deliver a research testbed dedicated to holistic research studies on energetical aspects of datacenters. Part of the Grid'5000 Nantes' site, this infrastructure is composed of probes that measure the power consumption of each server, each switch and each cooling system, and also measure the temperature at the front and the back of each servers. These sensors enable reasearch to cover a full spectrum of the energetical aspect of datacenters, such as cooling and power consumption depending of experimental conditions.

The testbed is connected to renewable energy sources (solar panels). This "green" datacenter will enable researchers to perform real experiment-driven studies on fields such as temperature based scheduling or "green" aware software (*i.e.*, software that take into account renewable energies and weather conditions).

6.7.4. SILECS

STACK Members are involved in the definition and bootstrap of the SILECS infrastructure. This infrastructure can be seen as a merge of the Grid'5000 and FIT testbeds with the goal of providing a common platform for experimental computer Science (Next Generation Internet, Internet of things, clouds, HPC, big data, etc.).

7. New Results

7.1. Resource Management

Participants: Mohamed Abderrahim, Adwait Jitendra Bauskar, Emile Cadorel, Hélène Coullon, Jad Darrous, David Espinel, Shadi Ibrahim, Thomas Lambert, Adrien Lebre, Jean-Marc Menaud, Alexandre Van Kempen.

In 2019, we achieved several contributions regarding the management of resources and data of cloud infrastructures, especially in a geo-distributed context (*e.g.*, Fog and Edge computing).

The first contributions are related to improvements of low-level building blocks. The following ones deal with geo-distributed considerations. Finally the last ones are related to capacity and placement strategies of distributed applications and scientific workflows.

In [15], we discuss how to improve I/O fairness and SSDs' utilization through the introduction of a NCQ-aware I/O scheduling scheme, NASS. The basic idea of NASS is to elaborately control the request dispatch of workloads to relieve NCQ conflict and improve NCQ utilization at the same time. To do so, NASS builds an evaluation model to quantify important features of the workload. In particular, the model first finds aggressive workloads, which cause NCQ conflict, based on the request size and the number of requests of the workloads. Second, it evaluates merging tendency of each workload, which may affect the bandwidth and cause NCQ conflict indirectly, based on request merging history. Third, the model identifies workloads with deceptive idleness, which cause low NCQ utilization, based on historical requests in I/O scheduler. Then, based on the model, NASS sets the request dispatch of each workload to guarantee fairness and improve device utilization: (1) NASS limits aggressive workloads to relieve NCQ conflict; (2) it adjusts merging of sequential workloads to improve bandwidth of the workloads while relieving NCQ conflict; and (3) it restricts request dispatch of I/O scheduler, rather than stopping request dispatch to improve NCQ utilization. We integrate NASS into four state-of-the-art I/O schedulers including CFQ, BFQ, FlashFQ, and FIOPS. The experimental results show that with NASS, I/O schedulers can achieve 11-23% better fairness and at the same time improve device utilization by 9-29%.

In [16], [28], we address the challenge related to the boot duration of virtual machines and containers in high consolidated cloud scenarios.This time, which can last up to minutes, is critical as it defines how an application can react w.r.t. demands' fluctuations (horizontal elasticity). Our contribution is the YOLO proposal (You Only Load Once). YOLO reduces the number of I/O operations generated during a boot process by relying on a boot image abstraction, a subset of the VM/container image that contains data blocks necessary to complete the boot operation. Whenever a VM or a container is booted, YOLO intercepts all read accesses and serves them directly from the boot image, which has been locally stored on fast access storage devices (e.g., memory, SSD, etc.). In addition to YOLO, we show that another mechanism is required to ensure that files related to VM/container management systems remain in the cache of the host OS. Our results show that the use of these two techniques can speed up the boot duration 2–13 times for VMs and 2 times for containers. The benefit on containers is limited due to internal choices of the docker design. We underline that our proposal can be easily applied to other types of virtualization (e.g., Xen) and containerization because it does not require intrusive modifications on the virtualization/container management system nor the base image structure.

Complementary to the previous contribution and in an attempt to demonstrate the importance of container image placement across edge servers, we propose and evaluate through simulation two novel container image placement algorithms based on k-Center optimization in [14]. In particular, we introduce a formal model to tackle down the problem of reducing the maximum retrieval time of container images, which we denote as MaxImageRetrievalTime. Based on the model, we propose KCBP and KCBP-WC, two placement algorithms which target reducing the maximum retrieval time of container images from any edge server. While KCBP is based on a k-Center solver (i.e., placing k facilities on a set of nodes to minimize the distance from any node to the closet facility) which is applied on each layer and its replicas (taking into account the storage capacities of the nodes), KCBP-WC uses the same principle but it tries to avoid simultaneous downloads from the same node. More precisely, if two layers are part of the same image, then they cannot be placed on the same nodes. We have implemented our proposed algorithms alongside two other state-of-the-art placement algorithms (i.e., Best-Fit and Random) in a simulator written in Python. Simulation results show that the proposed algorithms can outperform state-of- the-art algorithms by a factor of 1.1x to 4x depending on the characteristics of the networks.

In [13], we conduct experiments to thoroughly understand the performance of data-intensive applications under replication and EC. We use representative benchmarks on the Grid'5000 testbed to evaluate how analytic workloads, data persistency, failures, the back-end storage devices, and the network configuration impact their performances. While some of our results follow our intuition, others were unexpected. For example, disk and network contentions caused by chunks distribution and the unawareness of their functionalities are the main factor affecting the performance of data-intensive applications under EC, not data locality. An important outcome of our study is that it illustrates in practice the potential benefits of using EC in data-intensive clusters, not only in reducing the storage cost – which is becoming more critical with the wide adoption of high-speed storage devices and the explosion of generated and to be processed data – but also in improving the performance of data-intensive applications. We extended our work to Fog infrastructures in [31]. In particular, we empirically demonstrate the impact of network heterogeneity on the execution time of MR applications when running in the Fog.

In [5], we propose a first approach to deal with the data location challenges in geo-distribtued object stores. Existing solutions, relying on a distributed hash table to locate the data, are not efficient because location record may be placed far away from the object replicas. In this work, we propose to use a tree-based approach to locate the data, inspired by the Domain Name System (DNS) protocol. In our protocol, servers look for the location of an object by requesting successively their ancestors in a tree built with a modified version of the Dijkstra's algorithm applied to the physical topology. Location records are replicated close to the object replicas to limit the network traffic when requesting an object. We evaluate our approach on the Grid'5000 testbed using micro experiments with simple network topologies and a macro experiment using the topology of the French National Research and Education Network (RENATER). In this macro benchmark, we show that the time to locate an object in our approach is less than 15 ms on average which is around 20% shorter than using a traditional Distributed Hash Table (DHT).

In [20], we present the design, implementation, and evaluation of F-Storm, an FPGA-accelerated and general-purpose distributed stream processing system in the Edge. By analyzing current efforts to enable stream data processing in the Edge and to exploit FPGAs for data-intensive applications, we derive the key design aspects of F-Storm. Specifically, F-Storm is designed to: (1) provide a light-weight integration of FPGA with a DSP system in Edge servers, (2) make full use of FPGA resources when assigning tasks, (3) relieve the high overhead when transferring data between Java Virtual Machine (JVM) and FPGAs, and importantly (4) provide programming interface for users that enable them to leverage FPGA accelerators easily while developing their stream data applications. We have implemented F-Storm based on Storm. Evaluation results show that F-Storm reduces the latency by 36% and 75% for matrix multiplication and grep application compared to Storm. Furthermore, F-Storm obtains 1.4x, 2.1x, and 3.4x throughput improvement for matrix multiplication, grep application, and vector addition, respectively.

In [30], we discuss the main challengres related to the design and development of inter-site services for operating a massively distributed Cloud-Edge architecture deployed in different locations of the Internet backbone (i.e, network point of presences). More precisely, we discuss challenges related to the establishment of connectivity among several virtual infrastructure managers in charge of operating each site. Our goal is to initiate the discussion about the research directions on this field providing some interesting points to promote future work.

In [7], we focus on how to reduce the costly cross-rack data transferring in MapReduce systems. We observe that with high Map locality, the network is mainly saturated in Shuffling but relatively free in the Map phase. A little sacrifice in Map locality may greatly accelerate Shuffling. Based on this, we propose a novel scheme called Shadow for Shuffle-constrained general applications, which strikes a trade-off between Map locality and Shuffling load balance. Specifically, Shadow iteratively chooses an original Map task from the most heavily loaded rack and creates a duplicated task for it on the most lightly loaded rack. During processing, Shadow makes a choice between an original task and its replica by efficiently pre-estimating the job execution time. We conduct extensive experiments to evaluate the Shadow design. Results show that Shadow greatly reduces the cross-rack skewness by 36.6% and the job execution time by 26% compared to existing schemes.

In [6], we consider a complete framework for straggler detection and mitigation. We start with a set of metrics that can be used to characterize and detect stragglers including Precision, Recall, Detection Latency, Undetected Time and Fake Positive. We then develop an architectural model by which these metrics can be linked to measures of performance including execution time and system energy overheads. We further conduct a series of experiments to demonstrate which metrics and approaches are more effective in detecting stragglers and are also predictive of effectiveness in terms of performance and energy efficiencies. For example, our results indicate that the default Hadoop straggler detector could be made more effective. In certain case, Precision is low and only 55% of those detected are actual stragglers and the Recall, i.e., percent of actual detected stragglers, is also relatively low at 56%. For the same case, the hierarchical approach (i.e., a green-driven detector based on the default one) achieves a Precision of 99% and a Recall of 29%. This increase in Precision can be translated to achieve lower execution time and energy consumption, and thus higher performance and energy efficiency; compared to the default Hadoop mechanism, the energy consumption is reduced by almost 31%. These results demonstrate how our framework can offer useful insights and be applied in practical settings to characterize and design new straggler detection mechanisms for MapReduce systems.

In [21], we provide a general solution for workflow performance optimizations considering system variations. Specifically, we model system variations as time-dependent random variables and take their probability distributions as optimization input. Despite its effectiveness, this solution involves heavy computation overhead. Thus, we propose three pruning techniques to simplify workflow structure and reduce the probability evaluation overhead. We implement our techniques in a runtime library, which allows users to incorporate efficient probabilistic optimization into existing resource provisioning methods. Experiments show that probabilistic solutions can improve the performance by 51% compared to state-of-the-art static solutions while guaranteeing budget constraint, and our pruning techniques can greatly reduce the overhead of probabilistic optimization.

In [11], we propose a new strategy to schedule heteregeneous scientific workflows while minimizing the energy consumption of the cloud provider by introducing a deadline sensitive algorithm. Scheduling workflows in a cloud environment is a difficult optimization problem as capacity constraints must be fulfilled additionally to dependencies constraints between tasks of the workflows. Usually, work around the scheduling of scientific workflows focuses on public clouds where infrastructure management is an unknown black box. Thus, many works offer scheduling algorithms designed to select the best set of virtual machines over time, so that the cost to the end user is minimized. This paper presents the new v-HEFT-*deadline* algorithm that takes into account users deadlines to minimize the number of machines used by the cloud provider. The results show the real benefits of using our algorithm for reducing the energy consumption of the cloud provider.

In [9],we investigate how a monitoring service for Edge infrastructures should be designed in order to mitigate as much as possible its footprint in terms of used resources. Monitoring functions tend to become compute-, storage-and network-intensive, in particular because they will be used by a large part of applications that rely on real-time data. To reduce as much as possible the footprint of the whole monitoring service, we propose to mutualize identical processing functions among different tenants while ensuring their quality-of-service (QoS) expectations. We formalize our approach as a constraint satisfaction problem and show through micro-benchmarks its relevance to mitigate compute and network footprints.

In [22], we propose a generalization of the previous work. More precisely, weinvestigates whether the use of Constraint Programming (CP) could enable the development of a generic and easy-to-upgrade placement service for Fog/Edge Computing infrastructures. Our contribution is a new formulation of the placement problem, an implementation of this model leveraging Choco-solver and an evaluation of its scalability in comparison to recent placement algorithms. To the best of our knowledge, our study is the first one to evaluate the relevance of CP approaches in comparison to heuristic ones in this context. CP interleaves inference and systematic exploration to search for solutions, letting users on what matters: the problem description. Thus, our service placement model not only can be easily enhanced (deployment constraints/objectives) but also shows a competitive tradeoff between resolution times and solutions quality.

In [27], we present the first building blocks of a simulator to investigate placement challenges in Edge infrastructures. Efficiently scheduling computational jobs with data-sets dependencies is one of the most important challenges of fog/edge computing infrastructures. Although several strategies have been proposed, they have been evaluated through ad-hoc simulator extensions that are, when available, usually not maintained. This is a critical problem because it prevents researchers to-easily-conduct fair evaluations to compare each proposal. We propose to address this limitation throught the design and development of a common simulator. More precisely, in this research report, we describe an ongoing project involving academics and a high-tech company that aims at delivering a dedicated tool to evaluate scheduling policies in edge computing infrastructures. This tool enables the community to simulate various policies and to easily customize researchers/engineers' use-cases, adding new functionalities if needed. The implementation has been built upon the Batsim/SimGrid toolkit, which has been designed to evaluate batch scheduling strategies in various distributed infrastructures. Although the complete validation of the simulation toolkit is still ongoing, we demonstrate its relevance by studying different scheduling strategies on top of a simulated version of the Qarnot Computing platform, a production edge infrastructure based on smart heaters.

In [8], we propose an efficient graph partitioning method named Geo-Cut, which takes both the cost and performance objectives into consideration for large graph processing in geo-distributed DCs.Geo-Cut adopts two optimization stages. First, we propose a cost-aware streaming heuristic and utilize the one-pass streaming graph partitioning method to quickly assign edges to different DCs while minimizing inter-DC data communication cost. Second, we propose two partition refinement heuristics which identify the performance bottlenecks of geo-distributed graph processing and refine the partitioning result obtained in the first stage to reduce the inter-DC data transfer time while satisfying the budget constraint. Geo-Cut can be also applied to partition dynamic graphs thanks to its lightweight runtime overhead. We evaluate the effectiveness and efficiency of Geo-Cut using real-world graphs with both real geo-distributed DCs and simulations. Evaluation results show that Geo-Cut can reduce the inter-DC data transfer time by up to 79% (42% as the median) and reduce the monetary cost by up to 75% (26% as the median) compared to state-of-the-art graph partitioning methods with a low overhead.

7.2. Programming Support

Participants: Maverick Chardet, Hélène Coullon, Thomas Ledoux, Jacques Noyé, Dimitri Pertin, Simon Robillard, Hamza Sahli, Charlène Servantie.

Our contributions regarding programming support are divided in two topics. First, we focused on one specific challenge related to distributed software deployment: distributed software commissioning. We have proposed a useful approach for introducing model checking to help system operators design their parallel distributed software commissioning. Then, we focused on Fog formalization and we have proposed a fully graphical process algebraic formalism to design a Fog system.

In [12], MADA, a deployment approach to facilitate the design of efficient and safe distributed software commissioning is presented. MADA is built on top of the Madeus formal model that focuses on the efficient execution of installation procedures. Madeus puts forward more parallelism than other commissioning models, which implies a greater complexity and a greater propensity for errors. MADA provides a new specific language on top of Madeus that allows the developer to easily define the properties that should be ensured during the commissioning process. Then, MADA automatically translates the description to a time Petri net and a set of TCTL formulae. MADA is evaluated on the OpenStack commissioning.

About Fog formalization, we present a novel formal model defining spatial and structural aspects of Fog-based systems using Bigraphical Reactive Systems, a fully graphical process algebraic formalism [17]. The model is extended with reaction rules to represent the dynamic behavior of Fog systems in terms of self-adaptation. The notion of bigraph patterns is used in conjunction with boolean and temporal operators to encode spatio-temporal properties inherent to Fog systems and applications. The feasibility of the modelling approach is demonstrated via a motivating case study and various self-adaptation scenarios.

Overall, the number of contributions we made this year on the programming support topic is less significative than the previous one. However, we would like to underline that it does not reflect the recent efforts we put. In particular, the team has strongly developed the field of dynamic reconfiguration of distributed software systems and expects to get important results during 2020.

7.3. Energy-aware computing

Participants: Emile Cadorel, Hélène Coullon, Adrien Lebre, Thomas Ledoux, Jean-Marc Menaud, Jonathan Pastor, Dimitri Saingre, Yewan Wang.

Energy consumption is one of the major challenges of modern datacenters and supercomputers. Our works in Energy-aware computing can be categorized into two subdomains: Software level (SaaS, PaaS) and Infrastructure level (IaaS). At Software level, we worked on the general Cloud applications architectures and more recently on BlockChain-based solutions. At Infrastructure level, we worked this year on two directions: (i) investigating the thermal aspects in datacenters, and (ii) analyzing the energy footprint of geo-distributed plateforms.

In [11], the scheduling of heterogeneous scientific workflows while minimizing the energy consumption of the cloud provider is tackled by introducing a deadline sensitive algorithm. Scheduling workflows in a cloud environment is a difficult optimization problem as capacity constraints must be fulfilled additionally to dependencies constraints between tasks of the workflows. Usually, work around the scheduling of scientific workflows focuses on public clouds where infrastructure management is an unknown black box. Thus, many works offer scheduling algorithms designed to select the best set of virtual machines over time, so that the cost to the end user is minimized. This paper presents the new v-HEFT-*deadline* algorithm that takes into account users deadlines to minimize the number of machines used by the cloud provider. The results show the real benefits of using our algorithm for reducing the energy consumption of the cloud provider.

In [25], over the last year, both academic and industry have increase their work on blockchain technologies. Despite the potential of blockchain technologies in many areas, several obstacles are slowing down their development. In addition to the legal and social obstacles, technical limitations now prevent them from imposing themselves as a real alternative to centralised services. For example, several problems dealing with the scalability or the energy cost have been identified. That's why, a significant part of this research is focused on improving the performances (latency, throughput, energy footprint, etc.) of such systems. Unfortunately, Those projects are often evaluated with ad hoc tools and experimental environment, preventing reproducibility and easy comparison of new contribution to the state of the art. As a result, we notice a clear lack of tooling concerning the benchmarking of blockchain technologies. To the best of our knowledge only a few tools address such issues. Those tools often relies on the load generation aspect and omit some other important aspect of benchmark experiments such as reproducibility and the network emulation. We introduce BCTMark, a general framework for benchmarking blockchain technologies in an emulated environment in a reproductible way.

In [18], we present a deep evaluation about the power models based on CPU utilization. The influence of inlet temperature on models has been especially discussed. According to the analysis, one regression formula by using CPU utilization as the only indicator is not adequate for building reliable power models. First of all, Workloads have different behaviors by using CPU and other hardware resources in server platforms. Therefore, power is observed to have high dispersion for a fixed CPU utilization, especially at full workload. At the same time, we also find that, power is well proportional to CPU utilization within the execution of one single workload. Hence, applying workload classifications could be an effective way to improve model accuracy. Moreover, inlet temperature can cause surprising influence on model accuracy. The model reliability can be questioned without including inlet temperature data. In a use case, after including inlet temperature data, we have greatly improved the precision of model outputs while stressing server under three different ambient temperatures.

In [18], our physical experiments have shown that even under the same conditions, identical processors consume different amount of energy to complete the same task. While this manufacturing variability has been observed and studied before, there is lack of evidence supporting the hypotheses due to limited sampling data, especially from the thermal characteristics. In this article, we compare the power consumption among identical processors for two Intel processors series with the same TDP (Thermal Design Power) but from different generations. The observed power variation of the processors in newer generation is much greater than the older one. Then, we propose our hypotheses for the underlying causes and validate them under precisely controlled environmental conditions. The experimental results show that, with the increase of transistor densities, difference of thermal characteristics becomes larger among processors, which has non-negligible contribution to the variation of power consumption for modern processors. This observation reminds us of re-calibrating the precision of the current energy predictive models. The manufacturing variability has to be considered when building energy predictive models for homogeneous clusters.

In [3], we propose a model and a first implementation of a simulator in order to compare the energy footprint of different cloud architectures (single sites vs fully decentrlaized). Despite the growing popularity of Fog/Edge architectures, their energy consumption has not been well investigated yet. To move forward on such a critical question, we first introduce a taxonomy of different Cloud-related architectures. From this taxonomy, we then present an energy model to evaluate their consumption. Unlike previous proposals, our model comprises the full energy consumption of the computing facilities, including cooling systems, and the energy consumption of network devices linking end users to Cloud resources. Finally, we instantiate our model on different Cloud-related architectures, ranging from fully centralized to completely distributed ones, and compare their energy consumption. The results validates that a completely distributed architecture, because of not using intra-data center network and large-size cooling systems, consumes less energy than fully centralized and partly distributed architectures respectively. To the best of our knowledge, our work is the first one to propose a model that enables researchers to analyze and compare energy consumption of different Cloud-related architectures.

7.4. Security and Privacy

Participants: Mohammad-Mahdi Bazm, Fatima Zahra Boujdad, Wilmer Edicson Garzon Alfonso, Jean-Marc Menaud, Sirine Sayadi, Mario Südholt.

This year the team has provided two major contributions on security and privacy challenges in distributed systems. First, we have extended our model for secure and privacy-aware biomedical analyses, as well as started to explore the impact of the big-data analyses in this context. Second, we have contributed mitigation methods for Cloud-based side-channel attacks.

In [24], we have developed a methodology for the development of secure and privacy-aware biomedical analyses we motivate the need for real distributed biomedical analyses in the context of several ongoing projects, including the I-CAN project that involves 34 French hospitals and affiliated research groups. We present a set of distributed architectures for such analyses that we have derived from discussions with different medical research groups and a study of related work. These architectures allow for scalability, security/privacy and reproducibility properties to be taken into account. A predefined set of architectures allows medecins and biomedical engineers to define high-level distributed architectures for biomedical analyses that ensure strong security and constraints on private data. Architectures from this set can then be implemented with ease because of detailed, also predefined, detailed implementation templates. Finally, we illustrate how these architectures can serve as the basis of a development method for biomedical distributed analyses.

In [10] and [23], we presented a new taxonomy for container security with a particular focus on data transmitted through the virtualization boundary. Containerization is a lightweight virtualization technique reducing virtualization overhead and deployment latency compared to full VM; its popularity is quickly increasing. However, due to kernel sharing, containers provide less isolation than full VM. Thus, a compromised container may break out of its isolated context and gain root access to the host server. This is a huge concern, especially in multi-tenant cloud environments where we can find running on a single server containers serving very different purposes, such as banking microservices, compute nodes or honeypots. Thus, containers with specific security needs should be able to tune their own security level. Because OS-level defense approaches inherited from time-sharing OS generally requires administrator rights and aim to protect the entire system, they are not fully suitable to protect usermode containers. Research recently made several contributions to deliver enhanced security to containers from host OS level to (partially) solve these challenges. In this survey, we propose a new taxonomy on container defense at the infrastructure level with a particular focus on the virtualization boundary, where interactions between kernel and containers take place. We then classify the most promising defense frameworks into these categories.

Finally, we have leveraged an approach based on Moving Target Defense (MTD) theory to interrupt a cache-based side-channel attack between two Linux containers in the context of the Mohammad Mahdi's PhD thesis [1]. MTD allows us to make the configuration of system more dynamic and consequently more harder to attack by an adversary, by using shuffling at different level of system and cloud. Our approach does not need to carrying modification neither into the guest OS or the hypervisor. Experimental results show that our approach imposes very low performance overhead. We have also provided a survey on the isolation challenge and on the cache-based side-channel attacks in cloud computing infrastructures. We have developed different approaches to detect/mitigate cross-VM/cross-containers cache-based side-channel attacks. Regarding the detection of cache-based side-channel attacks, we have enabled their detection by leveraging Hardware performance Counters (HPCs) and Intel Cache Monitoring Technology (CMT) with anomaly detection approaches to identify a malicious virtual machine or a Linux container. Our experimental results show a high detection rate.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

Participants: Ronan-Alexandre Cherrueau, Marie Delavergne, Adrien Lebre [Contact point], Javier Rojas Balderrama, Matthieu Simonin.

Following the ENOS bilateral contract ("Contrat de Recherche Externalisé") between Orange and Inria (Sept 2017-Oct 2018), we agreed with Orange Labs to pursue this collaboration around a second contrat. This new contrat, which is going to last 18 months for a budget of 150K€, targets the following objectives:

- Strengthen the Enos framework and the resulting EnosLib solution (see Section 6.4 and Section 6.5).
- Define an experimental protocol allowing the automatozed and reproducible evaluation of an OpenStack instance in a WANWide context.
- Develop a DSL to reify location aspects at the CLI level in order to create new resources (image, VM, etc.) through a set of OpenStack instances while guaranteeing a notion of master copy.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. SysMics

Participants: Jean-Marc Menaud, Mario Südholt [coordinator].

The SysMics project aims at federating the NExT scientific community toward a common objective: anticipate the emergence of systems medicine by co-developing 3 approaches in population-scale genomics: genotyping by sequencing, cell-by-cell profiling and microbiome analysis. STACK investigates new means for secure and privacy-aware computations in the context of personalized medecine, notably genetic analyses.

This project is financed by the Nantes excellency initiative in Medecine and Informatics (NExT) from 2018-22.

9.1.2. SHLARC

Participants: Mario Südholt [coordinator], Sirine Sayadi.

The SHLARC project is an international network involving more than 20 partners from more than 15 countries located on four continents. The network aims at improving HLA imputation techniques in the domain of immunobiology, notably by investigation better computational methods for the correspoding biomedical analyses.

The ambition of the SHLARC is to bring together international expertise to solve essential questions on immune-related pathologies through innovative algorithms and powerful computation tool development. To achieve this goal, we determined 3 main objectives

- Data. By bringing together scientists from around the world, we will collectively increase the amount of SNP+HLA data available, both in terms of quantity and diversity.
- Applied mathematical and computer sciences. We will further optimize SNP-HLA imputation methods using the attribute-bagging HIBAG tool, and particularly for genetically diverse and admixed populations.
- Accessibility and service to the scientific community. Following the Haplotype Reference Consortium (HRC) initiative, the network envisions building a free, user-friendly webserver where researchers can access improved imputation protocols by simply uploading their data and obtaining the best possible HLA imputation for their dataset.

In this context, the STACK team is working on improved analysis techniques that harness distributed infrastructures.

This project is financed by the Nantes excellency initiative in Medecine and Informatics (NExT) from 2019-22.

9.1.3. Oncoshare

Participant: Mario Südholt [coordinator].

The ONCOSHARe project (ONCOlogy big data SHAring for Research) will demonstrate, through a multi-disciplinary cooperation within the Western CANCEROPOLE network, the feasibility and the added value of a Cancer Patient Centered Information Common for in-silico research. The STACK team will work on challenges to the security and the privacy of user data in this context.

This project is financed by three French regions from 2018-2021.

9.2. National Initiatives

9.2.1. Ademe

9.2.1.1. GL4MA

Participants: Brice Nédelec, Thomas Ledoux [coordinator].

The Green Label for Microservices Architecture (GL4MA) project aims to design and develop a technological platform (tools, framework, dedicated languages) for the self management of eco-responsible micro-service architectures for the Cloud. The experiments will be carried out through case studies provided by Sigma Informatique and the presence of renewable energy will initially be simulated. At the end of the project, the technological platform will be deployed as part of the CPER SeDuCe platform. This project is founded by the Ademe (call Perfecto) running for 18 months (starting in September 2019).

9.2.2. CominLabs laboratory of excellence

9.2.2.1. PrivGen

Participants: Fatima Zahra Boujdad, Mario Südholt [coordinator].

PrivGen ("Privacy-preserving sharing and processing of genetic data") is a three-year project that has been started in Oct. 2016 and is conducted by three partners: a team of computer scientists from the LATIM Inserm institute in Brest mainly working on data watermarking techniques, a team of geneticians from an Inserm institute in Rennes working on the gathering and interpretation of genetic data, and the STACK team. The project provides funding of 330 KEUR altogether with an STACK share of 120 KEUR.

The project considers challenges related to the outsourcing of genetic data that is in the Cloud by different stakeholders (researchers, organizations, providers, etc.). It tackles several limitations of current security solutions in the cloud, notably the lack of support for different security and privacy properties at once and computations executed at different sites that are executed on behalf of multiple stakeholders.

The partners are working on three main challenges:

- Mechanisms for a continuous digital content protection.
- Composition of security and privacy-protection mechanisms
- Distributed processing and sharing of genetic data.

The STACK team is mainly involved in providing solutions for the second and third challenges.

9.2.2.2. SeDuCe++

Participants: Jonathan Pastor, Jean-Marc Menaud [coordinator].

SeDuCe++ is an extended version of the SeDuCe project. Funded by the LS2N (CNRS), an allocated budget of 10K€ for one year, it aims at studying the energy footprint of extreme edge infrastructure.

9.2.3. ANR

9.2.3.1. GRECO (ANR)

Participants: Adrien Lebre [Contact point], Alexandre Van Kempen.

The GRECO project (Resource manager for cloud of Things) is an ANR project (ANR-16-CE25-0016) running for 42 months (starting in January 2017 with an allocated budget of 522K€, 90K€ for STACK).

The consortium is composed of 4 partners: Qarnot Computing (coordinator) and 3 academic research group (DATAMOVE and AMA from the LIG in Grenoble and STACK from Inria Rennes Bretagne Atlantique).

The goal of the GRECO project (https://anr-greco.net) is to design a manager for cloud of things. The manager should act at the IaaS, PaaS and SaaS layer of the cloud. To move forward to this objective, we have been designing a simulator to innovate in designing scheduling and data management systems. This simular leverage the Simgrid/PyBATSIM solution [27].

9.2.3.2. KerStream (ANR)

Participant: Shadi Ibrahim [Coordinator].

The KerStream project (Big Data Processing: Beyond Hadoop!) is an ANR JCJC (Young Researcher) project (ANR-16-CE25-0014-1) running for 48 months (starting in January 2017 with an allocated budget of 238K€).

The goal of the KerStream project is to address the limitations of Hadoop when running Big Data stream applications on large-scale clouds and do a step beyond Hadoop by proposing a new approach, called KerStream, for scalable and resilient Big Data stream processing on clouds. The KerStream project can be seen as the first step towards developing the first French middleware that handles Stream Data processing at Scale.

9.2.4. FSN

9.2.4.1. Hydda (FSN)

Participants: Hélène Coullon, Jean-Marc Menaud [coordinator].

The HYDDA project aims to develop a software solution allowing the deployment of Big Data applications (with hybrid design (HPC/CLoud)) on heterogeneous platforms (cluster, Grid, private Cloud) and orchestrators (Task scheduler like Slurm, Virtual orchestrator (like Nova for OpenStack or Swarm for Docker). The main questions we are investigating are :

- How to propose an easy-to-use service to host (from deployment to elimination) application components that are both typed Cloud and HPC?
- How propose a service that unifies the HPCaaS (HPC as a service) and the Infrastructure as a Service (IaaS) in order to offer resources on demand and to take into account the specificities of scientific applications?
- How optimize resources usage of these platforms (CPU, RAM, Disk, Energy, etc.) in order to propose solutions at the least cost?

9.2.5. CPER

9.2.5.1. SeDuCe

Participants: Adrien Lebre, Jean-Marc Menaud [coordinator], Jonathan Pastor.

The SeDuCe project (Sustainable Data Centers: Bring Sun, Wind and Cloud Back Together), aims to design an experimental infrastructure dedicated to the study of data centers with low energy footprint. This innovative data center will be the first experimental data center in the world for studying the energy impact of cloud computing and the contribution of renewable energy (solar panels, wind turbines) from the scientific, technological and economic viewpoints. This project is integrated in the national context of grid computing (Grid'5000), and the Constellation project, which will be an inter-node (Pays de la Loire, Brittany).

9.2.6. Inria Project Labs

9.2.6.1. DISCOVERY

Participants: Javier Rojas Balderrama, Hélène Coullon, Marie Delavergne, Shadi Ibrahim, Adrien Lebre [coordinator], Ronan-Alexandre Cherrueau, Matthieu Simonin, Alexandre Van Kempen.

To accommodate the ever-increasing demand for Utility Computing (UC) resources, while taking into account both energy and economical issues, the current trend consists in building larger and larger Data Centers in a few strategic locations. Although such an approach enables UC providers to cope with the actual demand while continuing to operate UC resources through centralized software system, it is far from delivering sustainable and efficient UC infrastructures for future needs.

The DISCOVERY initiative [10] aims at exploring a new way of operating Utility Computing (UC) resources by leveraging any facilities available through the Internet in order to deliver widely distributed platforms that can better match the geographical dispersal of users as well as the ever increasing demand. Critical to the emergence of such locality-based UC (also referred as Fog/Edge Computing) platforms is the availability of appropriate operating mechanisms. The main objective of DISCOVERY is to design, implement, demonstrate and promote a new kind of Cloud Operting System (OS) that will enable the management of such a large-scale and widely distributed infrastructure in an unified and friendly manner.

The consortium is composed of experts in the following research areas: large-scale infrastructure management systems, networking and P2P algorithms. Moreover, two key network operators, namely Orange and RENATER, are involved in the project.

By deploying and using a Fog/Edge OS on backbones, our ultimate vision is to enable large parts of the Internet to be hosted and operated by its internal structure itself: a scalable set of resources delivered by any computing facilities forming the Internet, starting from the larger hubs operated by ISPs, governments and academic institutions, to any idle resources that may be provided by end users.

STACK led the DISCOVERY IPL and contributes mainly around two axes: VM life cycle management and deployment/reconfiguration challenges.

The IPL ended in July 2019.

9.2.7. InriaHub

9.2.7.1. Mercury

Participants: Ronan-Alexandre Cherrueau, Adrien Lebre [coordinator], Matthieu Simonin.

STACK, in particular within the framework of the DISCOVERY initiative has been working on the massively distributed use case since 2013. With the development of several proof-of-concepts around OpenStack, the team has had the opportunity to start an InriaHub action. Named Mercury, the goal of this action is twofold: (i) support the research development made within the context of DISCOVERY and (ii) favor the transfer toward the OpenStack community.
Further information available at: http://beyondtheClouds.github.io.

The Mercury action ended in July 2019.

9.2.7.2. Apollo/Soyuz

Participants: Javier Rojas Balderrama, Ronan-Alexandre Cherrueau, Adrien Lebre [coordinator], Matthieu Simonin.

The Apollo/Soyuz is the second InriaHub action attached the DISCOVERY IPL. While Mercury aims mainly at supporting development efforts within the DISCOVERY IPL, the Apollo/Soyuz is focusing on the animation and the dissemination of the DISCOVERY activities within the different open-source ecosystem (*i.e.*, OpenStack, OPNFV, etc.). One additional engineer will join the current team in January 2019.
Further information available at: http://beyondtheClouds.github.io.

The Apollo/Soyuz ended in Dec 2019.

9.2.8. Fonds d’amorçage IMT Industrie du Futur 2017

9.2.8.1. aLIFE

Participants: Hélène Coullon [coordinator], Jacques Noyé.

[10] http://beyondtheclouds.github.io

As a follow-up of the aLIFE workshop (Nantes, Jan. 2018), organized in partnership with colleagues from IMT Atlantique and gathering both academic and industrial partners, we have written a booklet [29] summarizing the workshop discussions and proposing a shared vision of what software research could bring to Industry 4.0 initiatives.

9.2.9. Connect Talent

9.2.9.1. Apollo (Connect Talent)

Participant: Shadi Ibrahim [Coordinator].

The Apollo project (Fast, efficient and privacy-aware Workflow executions in massively distributed Data-centers) is an individual research project "Connect Talent" running for 36 months (starting in November 2017 with an allocated budget of 201K€).

The goal of the Apollo project is to investigate novel scheduling policies and mechanisms for fast, efficient and privacy-aware data-intensive workflow executions in massively distributed data-centers.

9.2.10. Etoiles Montantes

9.2.10.1. VeRDi

Participant: Hélène Coullon [Coordinator].

VeRDi is an acronym for Verified Reconfiguration Driven by execution. The VeRDi project is funded by the French region Pays De La Loire where Nantes is located. The project starts in November 2018 and ends on December 2020 with an allocated budget of 172800€.

It aims at addressing distributed software reconfiguration in an efficient and verified way. The aim of the VeRDi project is to build an argued disruptive view of the problem. To do so we want to validate the work already performed on the deployment in the team and extend it to reconfiguration.

9.3. International Initiatives

9.3.1. Inria International Labs

Inria@SiliconValley

Associate Team involved in the International Lab:

9.3.1.1. Hermes

Title: Accelerating the Performance of Multi-Site Scientific applications through Coordinated Data management.

International Partner (Institution - Laboratory - Researcher):

Lawrence Berkeley National Laboratory (United States) - Scientific Data Management Group - Suren Byna.

Start year: 2019

See also: http://hermes-ea2019.gforge.inria.fr.

Advances in computing, experimental, and observational facilities are enabling scientists to generate and analyze unprecedented volumes of data. A critical challenge facing scientists in this era of data deluge is storing, moving, sharing, retrieving, and gaining insight from massive collections of data efficiently. Existing data management and I/O solutions on high-performance computing (HPC) systems require significant enhancements to handle the three V's of Big Data (volume, velocity, and variety) in order to improve productivity of scientists. Even more challenging, many scientific Big Data and machine learning applications require data to be shared, exchanged, and transferred among multiple HPC sites. Towards overcoming these challenges, in this project, we aim at accelerating scientific Big Data application performance through coordinated data management that addresses performance limitations of managing data across multiple sites. In particular, we focus on challenges related to the management of data and metadata across sites, distributed burst buffers, and online data analysis across sites.

9.3.2. Inria International Partners

9.3.2.1. Informal International Partners

Huazhong university of Science and Technology (HUST): We collaborate on resource management for stream data applications in the edge, I/O scheduling for SDDs and network-aware task scheduling for MapReduce.

National University of Singapore (NUS): We collaborate on resource management for workflows in the clouds and optimizing graph processing in geo-distributed data-centers.

ShenZhen University: We collaborate on resource management for workflows in the clouds and optimizing graph processing in geo-distributed data-centers.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Suren Byna, a Staff Scientist in the Scientific Data Management Group at Lawrence Berkeley National Lab (LBNL), visited the STACK team from September 30 to October 4 2019. This visit was in the context of the Hermes Associate team.
- Twinkle Jain, a PhD student at Northeastern university, visited the STACK team from May 1 to July 31 2019. Twinkle was working with S. Ibrahim on stragglers mitigation in big data systems. The visit was funded by the ANR KerStream and the Apollo Connect Talent projects.

9.4.1.1. Internships

- Asha Begam Mohamed Mubarak, a master student at University of Rennes 1, joined the team as a research intern from April 2019 until August 2019. Her thesis was on fast Container Image Retrieval in the Edge.

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

HUST, China: From August 23 to September 2, S. Ibrahim visited the Services Computing Technology and System Lab at Huazhong university of Science and Technology.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

- A. Lebre co-organized the TILECS workshop (Towards an Infrastructure for Large-Scale Experimental Computer Science), Grenoble, July 2019.

10.1.2. Scientific Events: Selection

10.1.2.1. Chair of Conference Program Committees

- S. Ibrahim was the program chair of the IEEE BigDataSE 2019.
- S. Ibrahim was the program chair of the Smart Data-2019.
- S. Ibrahim was the track co-chair for the Cloud Computing Track of CCGrid 2019.

10.1.2.2. Member of the Conference Program Committees

- H. Coullon was a member of the program committees of CCGrid 2019 and ICCS 2019.
- S. Ibrahim was a member of the program committees of SC'19, Poster track of SC 2019, ICPP 2019, Cluster 2019, ICA3PP 2019, PDSW@SC'19, and HPBDC@IPDPS'19.

- A. Lebre was a member of the program comittees of ICC 2019, IC2E 2019, CCGRID 2019, Cluster 2019, and CloudCom 2019.
- T. Ledoux was a member of the program committees of the conference Compas'19, of the 1st Workshop on Service Quality and Quantitative Evaluation in new Emerging Technologies @ IC2E'19, CrossCloud'19@CCGrid, and ARM'19@Middleware.
- J.-M. Menaud was a member of the program committees of SMARTGREENS'19, SOFTCOM 19.
- M. Südholt was a member of the program committees of CCGrid'19 and CloudCom'19.

10.1.2.3. Member of the Conference Steering Committees

- A. Lebre is a member of the steering committee of the international conference of Fog and Edge Computing (ICFEC).
- M. Südholt is a member of the steering committee of the international conference Programming.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- A. Lebre is an Associate Editor of the IEEE Transactions on BigData.
- A. Lebre is an Associate Editor of the IEEE Transactions on Cloud Computing.
- S. Ibrahim is an Associate Editor of Springer Frontiers of Computer Science journal.
- M. Südholt is an Associate Editor of the journal Programming.

10.1.3.2. Reviewer - Reviewing Activities

- S. Ibrahim has been a reviewer for the following journals: Future Generation Computer Systems, IEEE Internet Computing.
- A. Lebre has been a reviewer for the IEEE Transactions on Cloud Computing journal.
- T. Ledoux has been a reviewer for the following journals: Journal of Systems Architecture - Elsevier and Future Generation Computer Systems.
- M. Südholt has been a reviewer for the journal Transactions of Software Engineering (IEEE TSE).

10.1.4. Invited Talks

- H. Coullon has given a talk to the WIDE Inria team, "Distributed Software Management: Efficiency, Software Engineering and Verification", Rennes, France, Aug. 2019.
- H. Coullon has given a talk to the joint LaMHa/LTP working group of the GDR GPL, "Efficient and Safe Distributed Software Commissioning", Paris, France, Nov. 2019.
- H. Coullon has given a talk to the Department of Computer Science at the University of Tromsø, the Arctic University of Norway, "Efficient and Safe Distributed Software Commissioning and Reconfiguration", Norway, Dec. 2019.
- A. Lebre has given a talk to the Inria Business Club in Paris, France, May 2019.
- A. Lebre has given a talk to the TILECS Workshop in Grenoble, France, July 2019.
- A. Lebre has given a talk to the Journées Clouds in Toulouse, France, Sept 2019.
- A. Lebre has given a talk to the Inria/Interdigital Workshop in Rennes, France, Dec. 2019.

10.1.5. Scientific Expertise

- A. Lebre is a member of the scientific committe of the joint lab between Inria and Nokia Bell Labs.

10.1.6. Research Administration

- A. Lebre is a member of the executive committee of the GDR CNRS RSD "Réseau et Système distribué" and Co-leader of the transversal action Virtualization and Clouds of this GDR since 2015.
- A. Lebre is a member of the executive and architect committees of the Grid'5000 GIS (Groupement d'intérêt scientifique).

- A. Lebre is a member of the executive committee of the <I/O> Lab, a joint lab between Inria and Orange Labs.
- J. Noyé is the Deputy Head of the Automation, Production and Computer Sciences department of IMT Atlantique.
- J.-M. Menaud is organizer of "Pôle Science du Logiciel et des Systèmes Distribués" in Laboratoire des Sciences du Numérique à Nantes (LS2N). He is involved in the GIS VITTORIA (VIrTual inTegrative Oncology Research and InnovAtion).
- J.-M. Menaud is involved in the GIS PERLE (Pôle d'Excellence de la Recherche Ligérienne en Energie).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- S. Ibrahim is the co-coordinator of the international Master's program in Cloud Computing and Services at University of Rennes 1.
- T. Ledoux is the head of the apprenticeship program in Software Engineering FIL (http://www.imt-atlantique.fr/formation/ingenieur-par-apprentissage/ingenieurs-specialite-ingenierie-logicielle). This 3-year program leads to the award of a Master degree in Software Engineering from the IMT Atlantique.
- H. Coullon is responsible for the Computer Science domain of the new apprenticeship program in Industry 4.0 (FIT) of IMT Atlantique. This 3-year program leads to the award of a Master degree in Industry 4.0 from the IMT Atlantique.

10.2.2. Supervision

- PhD: Mohammad Mahdi Bazm, co-director: J.M. Menaud, director: M. Südholt, "Architecture d'isolation unifiée et mécanismes de lutte contre les canaux auxiliaires pour infrastructures cloud décentralisées", Defended July 2019, the8th.
- Phd: Linh Thuy Nguyen, director: A. Lebre, "Fast delivery of Virtual Machines and Containers: Understanding and optimizing the boot operation", defended on Sept 2019, the 24th.
- PhD: Jad Darrous, advisor: S. Ibrahim, director: C. Perez (Avalon), "Scalable and Efficient Data Management in Distributed Clouds: Service Provisioning and Data Processing" Defended Dec 2019, the 17th.
- PhD: Dimitri Saingre, advisor: T. Ledoux, director: J-M. Menaud.
- PhD: Maverick Chardet, advisor: H. Coullon, director: C. Perez (Avalon).
- PhD: Emile Cadorel, advisor: H. Coullon, director: J-M. Menaud.
- PhD: Jolan Philippe, adviros: H. Coullon, M. Tisi (NaoMod), director: G. Sunye (NaoMod).
- PhD: Yewan Wang, advisor: J.-M. Menaud.
- PhD: Maxime Belair, advisor: J.-M. Menaud.
- PhD: Fatima-zahra Boujdad, advisor: M. Südholt.
- PhD: Wilmer Garzon, advisor: M. Südholt.
- PhD: Sirine Sayadi, advisor: M. Südholt.
- Postdoc: David Guyon, advisor: S. Ibrahim.
- Postdoc: Thomas Lambert, advisor: S. Ibrahim.
- Postdoc: Jonathan Pastor, advisor: J.-M. Menaud.
- Postdoc: Rémy Pottier, advisor: J.-M. Menaud.
- Postdoc: Simon Robillard, advisor: H. Coullon.

- Postdoc: Hamza Sahli, advisor: T. Ledoux.
- Postdoc: Alexandre Van Kempen: A. Lebre (until June 2018).
- Engineer: Ronan-Alexandre Cherrueau, advisor: A. Lebre.
- Engineer: Brice Nédelec, advisor: T. Ledoux.
- Engineer: Dimitri Pertin, advisor: H. Coullon (Sept, Oct 2019).
- Engineer: Javier Rojas Balderrama, advisor: M. Simonin/A. Lebre.
- Engineer: Charlène Servantie, advisor: H. Coullon.

10.2.3. Juries

- H. Coullon was a reviewer of the Master thesis committee of Jolan Philippe, "Systematic development of efficient programs on parallel data structures", Northern Arizona University USA, Feb. 05, 2019.
- H. Coullon was a reviewer of the PhD committee of Alexandre Da Silva Veith, "Quality of Service Aware Mechanisms for (Re)Configuring Data Stream Processing Applications on Highly Distributed Infrastructure", Univ. Lyon, Sept. 32, 2019.
- H. Coullon was a reviewer of the PhD committee of KsanderEJJAAOUANI, "Conception du modèle de programmation INKS pour la séparation des préoccupations algorithmiques et d'optimisation dans les codes de simulation numérique ; application à la résolution du système Vlasov/Poisson 6D", Univ. Stasbourg, Nov. 25, 2019.
- S. Ibrahim was a member of the PhD committee of Chaopeng GUO, "Energy-efficient Resource Provisioning for Cloud Databases", Université Paul Sabatier, Jun. 14, 2019.
- A. Lebre was a member of the PhD Committee of Ali Reza Zamani Zadeh Najari, "Scheduling Edge And In-Transit Computing Resources For Stream Processing Applications", University of Rutgers (USA), May 2019.
- A. Lebre was a member of the PhD Committee of Luke Bertot "Improving the simulation of IaaS Clouds", University of Strasbourg (France), June 2019.
- A. Lebre was a reviewer and member of the PhD Committee of Loic Perennou, "Virtual Machine Experience Design: A Predictive Resource Allocation Approach for Cloud Infrastructures". Conservatoire National des Arts et Metier Paris (France), Oct 2019.
- A. Lebre was a member of the PhD Committee of Genc Tato "Lazy and Locality-Aware Building blocks for Fog Middleware: A Service Discovery Use Case", University of Rennes (France), Dec 2019.
- T. Ledoux was a member of the PhD committee of Xinxiu Tao, "Reliability of changes in cloud environment at PaaS level", Univ. Grenoble Alpes, Jan. 29, 2019.
- T. Ledoux was a member of the PhD committee of Amir Teshome Wonjiga, "User-centric security monitoring in cloud environments", Univ. Rennes 1, Jun. 03, 2019.
- T. Ledoux was a reviewer of the PhD committee of Umar Ozeer, "Autonomic Resilience of Distributed IoT Applications in the Fog", Univ. Grenoble Alpes, Dec. 11, 2019.
- J.-M. Menaud was a member of the PhD committee of Léo Grange, "Gestion de centre de données avec sources d'énergies renouvelables intermittentes et incertaines", Univ. Toulouse, Oct. 3, 2019.

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

- S. Ibrahim, Online publication http://emergences.inria.fr/2019/newsletter-n59/l59-Kerstream: *Un intergiciel post-Hadoop pour gérer les flux de données*.

10.3.2. Articles and contents

As a follow-up of the aLIFE workshop (Nantes, Jan. 2018), organized in partnership with colleagues from IMT Atlantique and gathering both academic and industrial partners, Hélène Coullon and Jacques Noyé have participated to a booklet publication [29] summarizing the workshop discussions and proposing a shared vision of what software research could bring to Industry 4.0 initiatives.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] M.-M. BAZM. *Unified isolation architectures and mechanisms against side channel attacks for decentralized cloud infrastructures*, Université de Nantes (UNAM), July 2019, https://hal.inria.fr/tel-02417362

[2] T. L. NGUYEN. *Fast delivery of virtual machines and containers : understanding and optimizing the boot operation*, Ecole nationale supérieure Mines-Télécom Atlantique, September 2019, https://tel.archives-ouvertes.fr/tel-02418752

Articles in International Peer-Reviewed Journals

[3] E. AHVAR, A.-C. ORGERIE, A. LEBRE. *Estimating Energy Consumption of Cloud, Fog and Edge Computing Infrastructures*, in "IEEE Transactions on Sustainable Computing", April 2019, pp. 1-12 [*DOI :* 10.1109/TSUSC.2019.2905900], https://hal.archives-ouvertes.fr/hal-02083080

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Invited Conferences

[9] M. ABDERRAHIM, M. OUZZIF, K. GUILLOUARD, J. FRANÇOIS, A. LEBRE, C. PRUD'HOMME, X. LORCA. *Efficient Resource Allocation for Multi-tenant Monitoring of Edge Infrastructures*, in "PDP 2019 - 27th Euromicro International Conference on Parallel, Distributed and Network-Based Processing", Pavie, Italy, 27th Euromicro International Conference on Parallel, Distributed and Network-Based Processing, IEEE, 2019, pp. 1-8 [*DOI :* 10.1109/EMPDP.2019.8671621], https://hal.inria.fr/hal-01987946

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[17] H. SAHLI, T. LEDOUX, É. RUTTEN. *Modeling Self-Adaptive Fog Systems Using Bigraphs*, in "FOCLASA 2019 - 17th International Workshop on coordination and Self-Adaptativeness of Sotware applications", Oslo, Norway, September 2019, pp. 1-16, https://hal.inria.fr/hal-02271394

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Scientific Popularization

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