Activity Report 2022

Team MYRIADS

Design and Implementation of Autonomous Distributed Systems

Joint team with Centre Inria de l'Université de Rennes

D1 – Large Scale Systems

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Project-Team MYRIADS

Creation of the Project-Team: 2012 January 01

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1 Team members, visitors, external collaborators

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- Shadi Ibrahim [INRIA, Researcher]
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- Volodia Parol–Guarino [UNIV RENNES 1, from Feb 2022 until Jul 2022]

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- Angélique Jarnoux [INRIA]

Visiting Scientist

- Radita Tapaning Hesti Liem [RWTH AACHEN UNIV, from Apr 2022 until Nov 2022, PhD student]

External Collaborators

- Anne Blavette [CNRS]
- Louis Rilling [DGA]

2 Overall objectives

2.1 General Objectives

MYRIADS is a joint team with INRIA, CNRS, UNIVERSITY RENNES 1, INSA RENNES and ENS RENNES. It is part of IRISA (D1 department on large scale systems) and INRIA RENNES – BRETAGNE ATLANTIQUE.

The objective of MYRIADS is to design and implement systems for autonomous service and resource management in interconnected and distributed clouds. The team tackles the challenges of dependable application execution and efficient resource management in highly distributed clouds.

2.2 Context

The MYRIADS team research activities are conducted in the context of the future of Internet.

Internet of Services. Myriads of applications are provided to more than one billion users [1] all over the world. Over time, these applications are becoming more and more sophisticated, a given application being a composition of services likely to be executed on various sites located in different geographical locations. The Internet of Services is spreading all domains: home, administration, business, industry and science. Everyone is involved in the Internet of Services: citizens, enterprises, scientists are application, service and resource consumers and/or providers over the Internet.

Outsourcing. Software is provided as a service over the Internet. Myriads of applications are available online to billions of users as, for instance, *GoogleApps* (Gmail). After decades in which companies used to host their entire IT infrastructures in-house, a major shift is occurring where these infrastructures are outsourced to external operators such as Data Centers and Computing Clouds. In the Internet of Services, not only software but also infrastructure are delivered as a service. Clouds turned computing and storage into a utility. Just like water or electricity, they are available in virtually infinite amounts and their consumption can be adapted within seconds like opening or closing a water tap. The main transition, however, is the change in business models. Companies or scientists do not need to buy and operate their own data centers anymore. Instead, the compute and storage resources are offered by companies on a "pay-as-you-go" basis. There is no more need

[1] According to World Stats, there are 4.94 billion Internet users i.e., more than 60% of the total world population in December 2020.

for large hardware investments before starting a business. Even more, the new model allows users to adapt their resources within minutes, e.g., scale up to handle peak loads or rent large numbers of computers for a short experiment. The risk of wasting money by either under-utilization or undersized data centers is shifted from the user to the provider.

Sharing and Cooperation. Sharing information and cooperating over the Internet are also important user needs both in the private and the professional spheres. This is exemplified by various services that have been developed in the last decade. Peer-to-peer networks are extensively used by citizens in order to share musics and movies. A service like *Flickr* allowing individuals to share pictures is also very popular. Social networks such as *FaceBook* or *Linkedln* link millions of users who share various kinds of information within communities. Virtual organizations tightly connected to Grids allow scientists to share computing resources aggregated from different institutions (universities, computing centers...). The EGEE European Grid is an example of production Grid shared by thousands of scientists all over Europe.

2.3 Challenges

The term cloud was coined 15 years ago. Today cloud computing is widely adopted for a wide range of usage: information systems outsourcing, web service hosting, scientific computing, data analytics, back-end of mobile and IoT applications. There is a wide variety of cloud service providers (IaaS, PaaS, SaaS) resulting in difficulties for customers to select the services fitting their needs. Production clouds are powered by huge data centers that customers reach through the Internet. This current model raises a number of issues. Cloud computing generates a lot of traffic resulting in ISP providers needing to increase the network capacity. An increasing amount of always larger data centers consumes a lot of energy. Cloud customers experience poor quality of experience for highly interactive mobile applications as their requests are dealt with in data centers that are several hops away. The centralization of data in clouds also raises (i) security issues as clouds are a target of choice for attackers and (ii) privacy issues with data aggregation.

Recently new cloud architectures have been proposed to overcome the scalability, latency, and energy issues of traditional centralized data centers. Various flavors of distributed cloud computing are emerging depending on the resources exploited: resources in the core network (distributed cloud), resources at the edge of the network (edge clouds) and even resources in the swarms of people's devices (fog computing) enabling scalable cloud computing. These distributed clouds raise new challenges for resource and application management.

The ultimate goal of the Myriads team is making highly distributed clouds sustainable. By sustainability we mean green, efficient and secure clouds. We plan to study highly distributed clouds including edge clouds and fog computing. In this context, we will investigate novel techniques for greening clouds including the optimization of energy consumption in distributed clouds in the context of smart grids. As more and more critical information systems are outsourced in the cloud and personal data captured by sensors embedded in smart objects and smartphones are stored in the cloud, we will investigate security and privacy issues in two directions: cloud security monitoring and personal data protection in cloud-based IoT applications.

System research requires experimental validation based on simulation and/or prototyping. Reproducible experimentation is essential. We will contribute to the design and implementation of simulators well suited to the study of distributed clouds (architecture, energy consumption) and of large scale experimentation platforms for distributed systems enabling reproducible experiments.

3 Research program

3.1 Introduction

In this section, we present our research challenges along four work directions: resource and application management in distributed cloud and fog computing architectures for scaling clouds in Section 3.2, energy management strategies for greening clouds in Section 3.3, security and data protection aspects for securing cloud-based information systems and applications in Section 3.4, and methods for experimenting with clouds in Section 3.5.

3.2 Scaling fogs and clouds

3.2.1 Resource management in hierarchical clouds

The next generation of utility computing appears to be an evolution from highly centralized clouds towards more decentralized platforms. Today, cloud computing platforms mostly rely on large data centers servicing a multitude of clients from the edge of the Internet. Servicing cloud clients in this manner suggests that locality patterns are ignored: wherever the client issues his/her request from, the request will have to go through the backbone of the Internet provider to the other side of the network where the data center relies. Besides this extra network traffic and this latency overhead that could be avoided, other common centralization drawbacks in this context include limitations in terms of security/legal issues and resilience.

At the same time, it appears that network backbones are over-provisioned for most of their usage. This may advocate for placing computing resources directly within the backbone network. The general challenge of resource management for such clouds stands in trying to be locality-aware: for the needs of an application, several virtual machines may exchange data. Placing them *close* to each other can significantly improve the performance of the application they compose. More generally, building an overlay network that takes into account the hierarchical aspects of the platform without being a hierarchical overlay – which comes with load balancing and resilience issues – is a challenge by itself.

3.2.2 Resource management in fog computing architectures

Fog computing infrastructures are composed of compute, storage and networking resources located at the edge of wide-area networks, in immediate proximity to the end users. Instead of treating the mobile operator's network as a high-latency dumb pipe between the end users and the external service providers, fog platforms aim at deploying cloud functionalities *within* the mobile phone network, inside or close to the mobile access points. Doing so is expected to deliver added value to the content providers and the end users by enabling new types of applications ranging from Internet-of-Things applications to extremely interactive systems (e.g., augmented reality). Simultaneously, it will generate extra revenue streams for the mobile network operators, by allowing them to position themselves as cloud computing operators and to rent their already-deployed infrastructure to content and application providers.

Fog computing platforms have a very different geographical distribution compared to traditional clouds. While traditional clouds are composed of many reliable and powerful machines located in a very small number of data centers and interconnected by very high-speed networks, mobile edge cloud are composed of a very large number of points-of-presence with a couple of weak and potentially unreliable servers, interconnected with each other by commodity long-distance networks. This creates new demands for the organization of a scalable mobile edge computing infrastructure, and opens new directions for research.

The main challenges that we plan to address are:

- How should an edge cloud infrastructure be designed such that it remains scalable, fault-tolerant, controllable, energy-efficient, etc.?
- How should applications making use of edge clouds be organized? One promising direction is to explore the extent to which stream-data processing platforms such as Apache Spark and Apache Flink can be adapted to become one of the main application programming paradigms in such environments.
- How data should be stored and managed to facilitate the deployment of Fog infrastructures and IoT applications while taking into acccount the limited storage capacity.

3.2.3 Self-optimizing applications in multi-cloud environments

As the use of cloud computing becomes pervasive, the ability to deploy an application on a multi-cloud infrastructure becomes increasingly important. Potential benefits include avoiding dependence on a single vendor, taking advantage of lower resource prices or resource proximity, and enhancing application availability. Supporting multi-cloud application management involves two tasks. First, it involves selecting an initial multi-cloud application deployment that best satisfies application objectives and optimizes performance and cost. Second, it involves dynamically adapting the application deployment in order to react to changes in execution conditions, application objectives, cloud provider offerings, or resource prices. Handling price changes in particular is becoming increasingly complex. The reason is the growing trend of providers offering sophisticated, dynamic pricing models that allow buying and selling resources of finer granularities for shorter time durations with varying prices.

Although multi-cloud platforms are starting to emerge, these platforms impose a considerable amount of effort on developers and operations engineers, provide no support for dynamic pricing, and lack the responsiveness and scalability necessary for handling highly-distributed, dynamic applications with strict quality requirements. The goal of this work is to develop techniques and mechanisms for automating application management, enabling applications to cope with and take advantage of the dynamic, diverse, multi-cloud environment in which they operate.

The main challenges arising in this context are:

- selecting effective decision-making approaches for application adaptation,
- supporting scalable monitoring and adaptation across multiple clouds,
- performing adaptation actions in a cost-efficient and safe manner.

3.3 Greening clouds

The ICT (Information and Communications Technologies) ecosystem now approaches 5% of world electricity consumption and this ICT energy use will continue to grow fast because of the information appetite of Big Data, large networks and large infrastructures as Clouds that unavoidably leads to large power.

3.3.1 Smart grids and clouds

We propose exploiting Smart Grid technologies to come to the rescue of energy-hungry Clouds. Unlike in traditional electrical distribution networks, where power can only be moved and scheduled in very limited ways, Smart Grids dynamically and effectively adapt supply to demand and limit electricity losses (currently 10% of produced energy is lost during transmission and distribution).

For instance, when a user submits a Cloud request (such as a Google search for instance), this is routed to a data center that processes it, computes the answer, and sends it back to the user. Google owns several data centers spread across the world and for performance reasons, the center answering the user's request is more likely to be the one closest to the user. However, this data center may be less energy efficient. The request may have consumed less energy, or a different kind of energy (renewable or not), if it had been sent to a more distant data center. In this case, the response time would have been increased but maybe not noticeably: a different trade-off between quality of service (QoS) and energy-efficiency could have been adopted.

While Clouds come naturally to the rescue of Smart Grids for dealing with this big data issue, little attention has been paid to the benefits that Smart Grids could bring to distributed Clouds. To our knowledge, no previous work has exploited the Smart Grids potential to obtain and control the energy consumption of entire Cloud infrastructures from underlying facilities such as air conditioning equipment (which accounts for 30% to 50% of a data center's electricity bill) to network resources (which are often operated by several actors) and to computing resources (with their heterogeneity and distribution across multiple data centers). We aim at taking advantage of the opportunity brought by the Smart Grids to exploit renewable energy availability and to optimize energy management in distributed Clouds.

3.3.2 Energy cost models

Cloud computing allows users to outsource the computer resources required for their applications instead of using a local installation. It offers on-demand access to the resources through the Internet with a pay-as-you-go pricing model. However, this model hides the electricity cost of running these infrastructures.

The costs of current data centers are mostly driven by their energy consumption (specifically by the air conditioning, computing and networking infrastructures). Yet, current pricing models are usually static and rarely consider the facilities' energy consumption per user. The challenge is to provide a fair and predictable model to attribute the overall energy costs per virtual machine and to increase energy-awareness of users.

Another goal consists in better understanding the energy consumption of computing and networking resources of Clouds in order to provide energy cost models for the entire infrastructure including incentivizing cost models for both Cloud providers and energy suppliers. These models will be based on experimental measurement campaigns on heterogeneous devices. Inferring a cost model from energy measurements is an arduous task since simple models are not convincing, as shown in our previous work. We aim at proposing and validating energy cost models for the heterogeneous Cloud infrastructures in one hand, and the energy distribution grid on the other hand. These models will be integrated into simulation frameworks in order to validate our energy-efficient algorithms at larger scale.

3.3.3 Energy-aware users

In a moderately loaded Cloud, some servers may be turned off when not used for energy saving purpose. Cloud providers can apply resource management strategies to favor idle servers. Some of the existing solutions propose mechanisms to optimize VM scheduling in the Cloud. A common solution is to consolidate the mapping of the VMs in the Cloud by grouping them in a fewer number of servers. The unused servers can then be turned off in order to lower the global electricity consumption.

Indeed, current work focuses on possible levers at the virtual machine suppliers and/or services. However, users are not involved in the choice of using these levers while significant energy savings could be achieved with their help. For example, they might agree to delay slightly the calculation of the response to their applications on the Cloud or accept that it is supported by a remote data center, to save energy or wait for the availability of renewable energy. The VMs are black boxes from the Cloud provider point of view. So, the user is the only one to know the applications running on her VMs.

We plan to explore possible collaborations between virtual machine suppliers, service providers and users of Clouds in order to provide users with ways of participating in the reduction of the Clouds energy consumption. This work will follow two directions: 1) to investigate compromises between power and performance/service quality that cloud providers can offer to their users and to propose them a variety of options adapted to their workload; and 2) to develop mechanisms for each layer of the Cloud software stack to provide users with a quantification of the energy consumed by each of their options as an incentive to become greener.

3.4 Securing clouds

3.4.1 Security monitoring service level objectives

While the trend for companies to outsource their information system in clouds is confirmed, the problem of securing an information system becomes more difficult. Indeed, in the case of infrastructure clouds, physical resources are shared between companies (also called tenants) but each tenant controls only parts of the shared resources, and, thanks to virtualization, the information system can be dynamically and automatically reconfigured with added or removed resources (for example starting or stopping virtual machines), or even moved between physical resources (for example using virtual machine migration). Partial control of shared resources brings new classes of attacks between tenants, and security monitoring mechanisms to detect such attacks are better placed out of the tenant-controlled virtual information systems, that is under control of the cloud provider. Dynamic and automatic reconfigurations of the information system make it unfeasible for a tenant's security administrator to setup the security monitoring components to detect attacks, and thus an automated self-adaptable security monitoring service is required.

Combining the two previous statements, there is a need for a dependable, automatic security monitoring service provided to tenants by the cloud provider. Our goal is to address the following challenges to design such a security monitoring service:

1. to define relevant Service-Level Objectives (SLOs) of a security monitoring service, that can figure in the Service-Level Agreement (SLA) signed between a cloud provider and a tenant;
2. to design heuristics to automatically configure provider-controlled security monitoring software components and devices so that SLOs are reached, even during automatic reconfigurations of tenants' information systems;
3. to design evaluation methods for tenants to check that SLOs are reached.

Moreover in challenges 2 and 3 the following sub-challenges must be addressed:

- although SLAs are bi-lateral contracts between the provider and each tenant, the implementation of the contracts is based on shared resources, and thus we must study methods to combine the SLOs;
- the designed methods should have a minimal impact on performance.

3.4.2 Data protection in Cloud-based IoT services

The Internet of Things is becoming a reality. Individuals have their own swarm of connected devices (e.g. smartphone, wearables, and home connected objects) continually collecting personal data. A novel generation of services is emerging exploiting data streams produced by the devices' sensors. People are deprived of control of their personal data as they don't know precisely what data are collected by service providers operating on Internet (oISPs), for which purpose they could be used, for how long they are stored, and to whom they are disclosed. In response to privacy concerns the European Union has introduced, with the Global Data Protection Regulation (GDPR), new rules aimed at enforcing the people's rights to personal data protection. The GDPR also gives strong incentives to oISPs to comply. However, today, oISPs can't make their systems GDPR-compliant since they don't have the required technologies. We argue that a new generation of system is mandatory for enabling oISPs to conform to the GDPR. We plan to to design an open source distributed operating system for native implementation of new GDPR rules and ease the programming of compliant cloud-based IoT services. Among the new rules, transparency, right of erasure, and accountability are the most challenging ones to be implemented in IoT environments but could fundamentally increase people's confidence in oISPs. Deployed on individuals' swarms of devices and oISPs' cloud-hosted servers, it will enforce detailed data protection agreements and accountability of oISPs' data processing activities. Ultimately we will show to what extend the new GDPR rules can be implemented for cloud-based IoT services. In addition, we are also working on new approaches to allow the running of graph applications in geo-distributed Clouds while respecting the data protection regulations in different locations.

3.5 Experimenting with Clouds

Cloud platforms are challenging to evaluate and study with a sound scientific methodology. As with any distributed platform, it is very difficult to gather a global and precise view of the system state. Experiments are not reproducible by default since these systems are shared between several stakeholders. This is even worsened by the fact that microscopic differences in the experimental conditions can lead to drastic changes since typical Cloud applications continuously adapt their behavior to the system conditions.

3.5.1 Experimentation methodologies for clouds

We propose to combine two complementary experimental approaches: direct execution on testbeds such as Grid'5000, that is eminently convincing but rather labor intensive, and simulations (using *e.g.*, SimGrid) that are much more light-weight, but require careful assessments. One specificity of the Myriads team is that we are working on these experimental methodologies *per se*, raising the standards of *good experiments* in our community.

We plan to make SimGrid widely usable beyond research laboratories, in order to evaluate industrial systems and to teach the future generations of cloud practitioners. This requires to frame the specific concepts of Cloud systems and platforms in actionable interfaces. The challenge is to make the framework both easy to use for simple studies in educational settings while modular and extensible to suit the specific needs of advanced industrial-class users.

We aim at leveraging the convergence opportunities between methodologies by further bridging simulation and real testbeds. The predictions obtained from the simulator should be validated against some real-world experiments obtained on the target production platform, or on a similar platform. This (in)validation of the predicted results often improves the understanding of the modeled system. On the other side, it may even happen that the measured discrepancies are due to some mis-configuration of the real platform that would have been undetected without this (in)validation study. In that sense, the simulator constitutes a precious tool for the quality assurance of real testbeds such as Grid'5000.

Scientists need more help to make their Cloud experiments fully reproducible, in the sprit of Open Science exemplified by the HAL Open Archive, actively backed by Inria. Users still need practical solutions to archive, share and compare the whole experimental settings, including the raw data production (particularly in the case of real testbeds) and their statistical analysis. This is a long lasting task to which we plan to collaborate through the research communities gathered around the Grid'5000 and SimGrid scientific instruments.

Finally, since correction and performance can constitute contradictory goals, it is particularly important to study them jointly. To that extend, we want to bridge the performance studies, that constitute our main scientific heritage, to correction studies leveraging formal techniques. SimGrid already includes support to exhaustively explore the possible executions. We plan to continue this work to ease the use of the relevant formal methods to the experimenter studying Cloud systems.

3.5.2 Use cases

In system research, it is important to work on real-world use cases from which we extract requirements inspiring new research directions and with which we can validate the system services and mechanisms we propose. In the framework of our close collaboration with the Data Science Technology department of the Lawrence Berkeley National Lab (LBNL), we will investigate cloud usage for scientific data management. Next-generation scientific discoveries are at the boundaries of datasets, e.g., across multiple science disciplines, institutions and spatial and temporal scales. Today, data integration processes and methods are largely ad hoc or manual. A generalized resource infrastructure that integrates knowledge of the data and the processing tasks being performed by the user in the context of the data and resource lifecycle is needed. Clouds provide an important infrastructure platform that can be leveraged by including knowledge for distributed data integration.

4 Application domains

4.1 Main application domains

The Myriads team investigates the design and implementation of system services. Thus its research activities address a broad range of application domains. We validate our research results with selected use cases in the following application domains:

- Smart city services,
- Smart grids,
- Energy and sustainable development,
- Home IoT applications,
- Bio-informatics applications,
- Data science applications,
- Computational science applications,
- Numerical simulations.

5 Social and environmental responsibility

5.1 Footprint of research activities

Anne-Cécile Orgerie is involved in the CNRS GDS EcoInfo that deals with reducing environmental and societal impacts of Information and Communications Technologies from hardware to software aspects. This group aims at providing critical studies, lifecycle analyses and best practices in order to reduce the environmental impact of ICT equipment in use in public research organizations.

5.2 Impact of research results

One of the research axes of the team consists in measuring and decreasing the energy consumption of Cloud computing infrastructures. The work associated to this axis contributes to increasing the energy efficiency of distributed infrastructures. This work has been conducted in particular in the CNRS 80Prime DECORUS project.

In the context of the CNRS RI/RE projects, work is also conducted on the current challenges of the energy sector and more specifically on the smart digitization of power grid management through the joint optimization of electricity generation, distribution and consumption. This work aims to optimize the computing infrastructure in charge of managing the electricity grids: guaranteeing their performance while minimizing their energy consumption.

In the CNRS FACTO project, the energy aspect of a sustainable smart home is studied by reducing the oversized number of wireless technologies that is actually connecting all the devices. This work aims to propose a versatile network based on only one optimized and energy efficient technology (Wi-Fi 7) that could meet all connected devices requirements.

The Myriads team also engaged in the Inria FrugalCloud challenge, in collaboration with the OVH-cloud company. The objective is to participate in the end-to-end eco-design of Cloud platforms in order to reduce their environmental impact.

6 Highlights of the year

- Anne-Cécile Orgerie was promoted to a Directrice de Recherche position, and she remains in the Myriads team.
- Cédric Tedeschi was promoted to a Full Professor position, and he remains in the Myriads team.
- François Lemercier was hired as an Associate Professor by the University of Rennes 1, and he remains in the team as a new permanent member.

6.1 Awards

- Shadi Ibrahim was honored as an ACM Distinguished Member for outstanding scientific contributions to computing.
- The paper entitled “Influence of Communication Technologies in Smart Grid Power Congestion Management” and authored by Adrien Gougeon, François Lemercier, Anne Blavette and Anne-Cécile Orgerie received the best paper award at the 18th IEEE International Conference on Green Computing and Communications (GreenCom).

7 New software and platforms

7.1 New software

7.1.1 SimGrid

Keywords: Large-scale Emulators, Grid Computing, Distributed Applications

Scientific Description: SimGrid is a toolkit that provides core functionalities for the simulation of distributed applications in heterogeneous distributed environments. The simulation engine uses algorithmic and implementation techniques toward the fast simulation of large systems on a single machine. The models are theoretically grounded and experimentally validated. The results are reproducible, enabling better scientific practices.

Its models of networks, cpus and disks are adapted to (Data)Grids, P2P, Clouds, Clusters and HPC, allowing multi-domain studies. It can be used either to simulate algorithms and prototypes of applications, or to emulate real MPI applications through the virtualization of their communication, or to formally assess algorithms and applications that can run in the framework.

The formal verification module explores all possible message interleavings in the application, searching for states violating the provided properties. We recently added the ability to assess liveness properties over arbitrary and legacy codes, thanks to a system-level introspection tool that provides a finely detailed view of the running application to the model checker. This can for example be leveraged to verify both safety or liveness properties, on arbitrary MPI code written in C/C++/Fortran.

Functional Description: SimGrid is a toolkit that provides core functionalities for the simulation of distributed applications in heterogeneous distributed environments. The simulation engine uses algorithmic and implementation techniques toward the fast simulation of large systems on a single machine. The models are theoretically grounded and experimentally validated. The results are reproducible, enabling better scientific practices.

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News of the Year: There were 3 major releases in 2022. The SimDag API for the simulation of the scheduling of Directed Acyclic Graphs has been dropped and replaced by called SimDag++ which provides the different features of SimDag directly on top of S4U. We also dropped the old and clumsy Lua bindings to create platforms in a programmatic way. It can be done in C++ in a much cleaner way now, which motivates this suppression. The C++ platform description has been improved to reject forbidden topologies, improve exporting for visualization, and allow users to dynamically change injected costs for MPI_* operations. The Python API to S4U has been extended. A new solver for parallel task (BMF) has been introduced and provides with more realistic sharing of heterogeneous resources compared to the fair bottleneck solver used by ptask_L07. Although this is still ongoing work, this paves the way to efficient macroscopic modeling of streaming activities and parallel applications. The internals of the Model Checker have been heavily reworked and new test suite from the MPI Bugs Initiative (MBI) are now used. The documentation was thoroughly overhauled to ease the use of the framework. We also pursued our efforts to improve the overall framework, through bug fixes, code refactoring and other software quality improvement.

URL: https://simgrid.org/

Contact: Martin Quinson

Participants: Adrien Lebre, Anne-Cécile Orgerie, Arnaud Legrand, Augustin Degomme, Arnaud Giersch, Emmanuelle Saillard, Frédéric Suter, Jonathan Pastor, Martin Quinson, Samuel Thibault

Partners: CNRS, ENS Rennes

7.1.2 Tansiv

Name: Time-Accurate Network Simulation Interconnecting Vms

Keywords: Operating system, Virtualization, Cloud, Simulation, Cybersecurity

Functional Description: Tansiv: Time-Accurate Network Simulation Interconnecting Virtual machines (VMs). Tansiv is a novel way to run an unmodified distributed application on top of a simulated network in a time accurate and stealth way. To this aim, the VMs execution is coordinated (interrupted and restarted) in order to garantee accurate arrival and transfer of network packets while ensuring realistic time flow within the VMs. The initial prototype uses Simgrid for simulating the data transfer and control the execution of the VMs. Also, Qemu is used to encapsulate the application, intercept the network traffic and enforce the interruption decision. Tansiv can be used in various situations: malware analysis (e.g. to defeat malware evasion technique based on network timing measures) or analysis of an application on a geo-distributed context.

Contact: Louis Rilling

Partner: DGA-MI

7.1.3 EnOSlib

Name: 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 ...

URL: `https://discovery.gitlabpages.inria.fr/enoslib/`

Publications: hal-01664515, hal-01689726

Contact: Mathieu Simonin

8 New results

8.1 Scaling Clouds

8.1.1 Fog computing platform design

Participants: Chih-Kai Huang, Guillaume Pierre, Paulo Souza.

There does not yet exist any reference platform for fog computing platforms. We therefore investigated how Kubernetes could be adapted to support the specific needs of fog computing platforms.

To allow Kubernetes to become a major platform for geo-distributed fog computing, an important and currently missing technique is the migration of Kubernetes pods across different servers located in different locations. In particular we focused on the problem of dynamically migrating running applications from one system node to another (potentially in a different location). Our technique migrates Kubernetes pods transparently to the application and to its users, and in particular keeps existing network connections open across the migration [12]. Application migration in geo-distributed fog computing infrastructure was the overall topic of Paulo Souza Junior's PhD which was defended in November 2022 [18].

An interesting technology for extending Kubernetes to large-scale geo-distributed scenarios is Kubernetes Federations (KubeFed), which allow one to aggregate resources provided by multiple independent Kubernetes clusters in various locations. We however demonstrated that these federation suffer from scalability issues due in particular to the amount of monitoring information they need to collect from the member clusters to make proper scheduling decisions. We therefore proposed a new technique based on metrics agregation and deduplication to reduce the volume of monitoring traffic up to 99% without impacting the quality of scheduling decisions [10].

Finally, we proposed algorithms to allow a fog computing platform based on Kubernetes to dynamically add and exploit new computing resources in case an overload is detected in some part of the system [4], and reported on the FogGuru hackathon (26-28 March 2021) [5].

8.1.2 Advanced data management for fast and reliable data access in shared infrastructures

Participants: Shadi Ibrahim.

Ensuring fast and reliable data accesses remain challenging problems in distributed Clouds and Fogs, where the infrastructure is heterogeneous and data and storage devices are shared by various applications.

Replication has been successfully employed and practiced in large-scale distributed storage systems to ensure high data availability and to improve data access performance under high load. However, with the relentless growth of generated and collected data, replication has become expensive not only in terms of storage cost but also in terms of network cost and hardware cost. Traditionally, erasure coding (EC) is employed as a cost-efficient alternative to replication when high access latency to the data can be tolerated. However, with the continuous reduction in its CPU overhead, EC is performed on the critical path of data access. For instance, EC has been integrated into the last major release of Hadoop Distributed File System (HDFS) which is the primary storage backend for data analytic frameworks (e.g., Hadoop, Spark, etc.). In this work [7], we study the performance of (concurrent) data accesses (write and read applications) under erasure coding and replication in a complementary and contrast approach. Our analysis indicates that EC is a feasible solution for data-intensive applications and it can outperform replication in many scenarios. Furthermore, we demonstrate that it is the block placement algorithm in HDFS that mostly impacts the performance under EC.

Due to their high access performance and decreasing prices, Solid State Devices (SSDs) are gradually replacing disks in cloud platforms. Unfortunately, the performance benefit of SSDs is still not fully exploited when applications run in containerized environments. Unfortunately, the I/O stack of the physical host overlooks the layered and independent nature of containers, thus I/O operations require expensive file redirect (between the storage driver, Overlay2/EXT4, and the virtual file system, VFS) and are scheduled sequentially. To this end, we introduce a Container-aware I/O stack (CAST) [13]. CAST is made up of Layer-aware VFS (LaVFS) and Container-aware Native File System (CaFS). LaVFS locates files based on layer information and enables simultaneous Copy-on-Write (CoW) operations and thus avoids the overhead of searching and modifying files. CaFS, on the other hand, provides contention-free ac- cess by designing fine-grain resource allocation at the native file system.

Finally, in the framework of the Hermes Associate team and the context of the ongoing collaboration between the Myriads project team at Inria and Lawrence Berkeley National Laboratory, we conduct a comprehensive study to characterize of I/O patterns in scientific applications and describe how those patterns are represented, used, and transformed as we traverse the HPC I/O stack. A scientific paper on this topic is submitted for publication.

8.1.3 Data Processing at scale

Participants: Shadi Ibrahim.

The past decade has witnessed a tremendous increase in the deployment of Big Data analytic systems in large-scale environments to meet the ever growing size and velocity of data. In the context of the ANR KerStream project, we focus on improving the performance of Big Data applications when running at large-scale infrastructures while addressing performance variability and data partitioning.

Performance variability in large-scale environments causes stragglers (tasks performing relatively slower than other tasks) which result in a severe degradation in performance. Speculative execution can significantly improve the performance of Big Data applications by launching other copies of stragglers. Stragglers detection plays an important role in the effectiveness of speculative execution. The methods employed to detect stragglers use the information extracted from the last received heartbeats which may be outdated when triggering detection. This, in turn, can mislead Big Data analytic systems to make wrong detection with high inaccuracy. To shed the light on this issue, we carry out extensive simulations to identify how heartbeat arrival, task starting times, and detection methods impact the accuracy of stragglers detection in Big Data analytic systems [11]. We reveal that the asynchrony in heartbeat arrivals not only lead to marking normal tasks as stragglers (false positives) but can also result in overlooking real stragglers (false negatives). In addition, with Thomas Lambert and Sami Djouadi (a master intern co-supervised by Myraids and COAST), we conduct an extensive analysis on recent production cluster traces from Alibaba to prove the prevalence of stragglers and understand their impact in large-scale production clusters.

Data-intensive applications usually consist of multiple computation stages where data flows among them. Data partitioning across tasks and skew mitigation contribute significantly to their performance. While previous efforts have focused on only two-stage applications, we showcase a comprehensive analysis of the interplay between data partitioning, data placement and the parallelism degree of the application. Part of the results were presented in a work-in-progress paper [15] and a full scientific paper is in preparation.

8.1.4 Geo-distributed graph data processing

Participants: Shadi Ibrahim.

Graph processing is a popular computing model for big data analytics. Emerging big data applications are often maintained in multiple geographically distributed (geo-distributed) data centers (DCs) to provide low-latency services to global users. Graph processing in geo-distributed DCs suffers from costly inter-DC data communications. Furthermore, due to increasing privacy concerns, geo-distribution imposes diverse, strict, and often asymmetric privacy regulations that constrain geo-distributed graph processing. Existing graph processing systems fail to address these two challenges.

In this collaborative work, we design and implement PGPregel [14], which is an end-to-end system that provides privacy-preserving graph processing in geo-distributed DCs with low latency and high utility. To ensure privacy, PGPregel smartly integrates Differential Privacy into graph processing systems with the help of two core techniques, namely sampling and combiners, to reduce the amount of inter-DC data transfer while preserving good accuracy of graph processing results. We implement our design in Giraph and evaluate it in real cloud DCs. Results show that PGPregel can preserve the privacy of graph data with low overhead and good accuracy.

8.1.5 Geo-distributed data stream processing

Participants: Khaled Arsalane, Davaadorj Battulga, Alessio Pagliari, Guillaume Pierre, Cédric Tedeschi.

Although data stream processing platforms such as Apache Flink are widely recognized as an interesting paradigm to process IoT data in fog computing platforms, the existing performance models that capture stream processing in geo-distributed environments are theoretical works only, and have not been validated against empirical measurements. In previous work we developed an auto-scaling mechanism which can dynamically add or remove resources to adjust the processing capacity to wide variations in the intensity of the workload. However, in a fog computing environment additional resources may not always be available. Similarly some streaming applications cannot scale horizontally. In such situations it becomes useful to exploit transprecision where the precision as well as the compute intensity can be reduced when necessary. We proposed a dual-controler autoscaler which exploits both horizontal scalability and transprecision to maintain an application's processing capacity. This work is currently under evaluation.

In the context of Davaadorj Battulga's PhD thesis, we are exploring mechanisms to bring stream processing applications in a geo-distributed environment. We base our approach on the collaboration of multiple, geo-distributed stream processing engines. In 2022, we continued working on the autonomous decentralized adaptation of such a collaborative platform. In particular, we designed a fully-decentralized adaptation algorithm for the migration of jobs composing a stream processing pipeline. A software prototype of it was built and experimented over an emulated geo-distributed platform based on Grid'5000.

8.1.6 Fault tolerance for Function-as-a-Service environments

Participants: Yasmina Bouizem, Christine Morin, Nikos Parlavantzas.

Recent years have seen the widespread adoption of serverless computing, and in particular, Function-as-a-Service (FaaS) systems. These systems enable users to execute arbitrary functions without managing underlying servers. One of the main challenges of FaaS systems is providing fault tolerance for the deployed functions. The basic fault tolerance mechanism in current FaaS platforms is automatically retrying function invocations. Although the retry mechanism is well-suited for transient faults, it incurs delays in recovering from other types of faults, such as node crashes. The goal of this work is to provide high availability for FaaS applications for different types of faults.

To this end, we have proposed the integration into FaaS frameworks of additional fault-tolerance mechanisms, beyond the basic retry mechanism. The mechanisms are based on passive and active replication and were integrated in Fission, a well-known, open source framework. We provided a detailed experimental comparison of the proposed mechanisms in terms of performance, availability, and resource consumption, both in normal functioning and under different failure scenarios. We also provided insights on how to select fault-tolerance mechanisms based on the application type and performance and availability requirements [19]. The work was performed in the context of the thesis of Yasmina Bouizem which was defended in June 2022 [17].

8.1.7 Flexible function placement for Function-as-a-Service in the fog

Participants: Volodia Parol-Guarino, Nikos Parlavantzas.

Function-as-a-Service (FaaS) is a compelling programming model for developing applications that run on fog infrastructures. FaaS applications are composed of ephemeral, event-triggered functions, which can be flexibly deployed along the Cloud-to-thing continuum. However, deciding where to place those functions in the fog poses many challenges, including the heterogeneity of fog resources and the dynamism and variability of FaaS workloads combined with the performance requirements of FaaS applications. Another challenge is that fog nodes are typically owned by different entities and thus a mechanism to incentivize them to contribute their resources is needed.

To address these challenges, we propose a market-based approach for placing FaaS applications in the fog. Customers submit function placement requests including latency and resource requirements. The framework then organizes auctions to determine the nodes that will host the functions and associated payments. We developed a proof-of-concept implementation of the framework using Kubernetes and OpenFaaS, and a publication on the topic is under preparation. This research was initiated as the internship of Volodia Parol-Guarino (February-July 2022). The research is continuing as part of the thesis project of Volodia Parol-Guarino, started in October 2022.

8.1.8 Reliable fog platforms in adverse natural environments

Participants: Marin Bertier, Cédric Tedeschi.

An interesting use-case for fog computing platforms is environmental monitoring to help Earth Sciences researchers (biologists, hydrologists, etc.) measure and understand specific natural environments. A fog platform in this context needs to support the needs of a wide range of applications which potentially compete for limited available computing resources, and exhibit self-management capabilities to remain operational with minimal human intervention despite potentially adverse execution conditions such as limited energy resources. Members of the Magellan project are involved in the TERRA FORMA PIA3 project which will give us the opportunity to deploy and test our fog platform technologies in real challenging environments.

8.1.9 Modeling cloud infrastructures

Participants: Clément Courageux-Sudan, Anne-Cécile Orgerie, Martin Quinson.

Wi-Fi networks are extensively used to provide Internet access to end-users and to deploy applications at the edge. By playing a major role in modern networking, Wi-Fi networks are getting bigger and denser. However, studying their performance at large-scale and in a reproducible manner remains a challenging task.

This year, we introduced a new Wi-Fi model for large-scale simulations. This model, based on flow-level simulation and integrated in SimGrid, requires fewer computations than state-of-the-art models to estimate bandwidth sharing over a wireless medium, leading to better scalability. The study shows that our approach yields to performance evaluations that are close to the ones of the classical ns-3 simulator while improving the runtime of simulations by several orders of magnitude [6].

8.2 Greening Clouds

8.2.1 Energy Models for Cloud infrastructures

Participants: Anne-Cécile Orgerie, Martin Quinson
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Cloud computing allows users to outsource the computer resources required for their applications instead of using a local installation. It offers on-demand access to the resources through the Internet with a pay-as-you-go pricing model. However, this model hides the electricity cost of running these infrastructures.

Vectorized instructions were introduced to improve the performance of applications. However, they come at the cost of an increase in the power consumption. As a consequence, processors are designed to limit their frequency when such instructions are used in order to respect the thermal design power limit. We studied and compare the impact of thermal design power and SIMD instructions on performance, power and energy consumption of processors and memory. The study shows that, because of processor frequency, performance and power consumption are strongly related to thermal design power [3].

The fine-grain measurements lead us to propose higher-level models that have been used to compare different Cloud architectures (from fog and edge to centralized clouds) in terms of energy consumption on a given scenario [2].

8.2.2 End-to-end energy models for the Internet of Things

Participants: Clément Courageux-Sudan, Anne-Cécile Orgerie, Martin Quinson.

The development of IoT (Internet of Things) equipment, the popularization of mobile devices, and emerging wearable devices bring new opportunities for context-aware applications in cloud computing environments. The disruptive potential impact of IoT relies on its pervasiveness: it should constitute an integrated heterogeneous system connecting an unprecedented number of physical objects to the Internet. Among the many challenges raised by IoT, one is currently getting particular attention: making computing resources easily accessible from the connected objects to process the huge amount of data streaming out of them.

While computation offloading to edge cloud infrastructures can be beneficial from a Quality of Service (QoS) point of view, from an energy perspective, it is relying on less energy-efficient resources than centralized Cloud data centers. On the other hand, with the increasing number of applications moving on to the cloud, it may become untenable to meet the increasing energy demand which is already reaching worrying levels. Edge nodes could help to alleviate slightly this energy consumption as they could offload data centers from their overwhelming power load and reduce data movement and network traffic. In particular, as edge cloud infrastructures are smaller in size than centralized data center, they can make a better use of renewable energy.

We investigate the end-to-end energy consumption of IoT platforms. Our aim is to evaluate, on concrete use-cases, the benefits of edge computing platforms for IoT regarding energy consumption. We aim at proposing end-to-end energy models for estimating the consumption when offloading computation from the objects to the Cloud, depending on the number of devices and the desired application QoS.

We also started to work on the environmental impacts of 5G networks [20].

8.2.3 Exploiting renewable energy in distributed clouds

Participants: Anne Blavette, Emmanuel Gnibga, Anne-Cécile Orgerie.

The growing appetite of Internet services for Cloud resources leads to a consequent increase in data center (DC) facilities worldwide. This increase directly impacts the electricity bill of Cloud providers. Indeed, electricity is currently the largest part of the operation cost of a DC. Resource over-provisioning, energy non-proportional behavior of today's servers, and inefficient cooling systems have been identified as major contributors to the high energy consumption in DCs.

In a distributed Cloud environment, on-site renewable energy production and geographical energy-aware load balancing of virtual machines allocation can be associated to lower the brown (i.e. not renewable) energy consumption of DCs. Yet, combining these two approaches remains challenging in current distributed Clouds. Indeed, the variable and/or intermittent behavior of most renewable sources – like solar power for instance – is not correlated with the Cloud energy consumption, that depends on physical infrastructure characteristics and fluctuating unpredictable workloads.

8.2.4 Smart Grids

Participants: Anne Blavette, Adrien Gougeon, François Lemercier, Anne-Cécile Orgerie, Martin Quinson.

Smart grids allow to efficiently perform demand-side management in electrical grids in order to increase the integration of fluctuating and/or intermittent renewable energy sources in the energy mix. In this work, we consider the computing infrastructure that controls the smart grid. This infrastructure comprises communication and computing resources to allow for a smart management of the electrical grid. In particular, we study the influence of communication latency over a shedding scenario on a small-scale electrical network. Our results show that latency may have a significant impact on energy management strategies in terms of performance for the smart grid, and that it should be considered when designing such strategies [8].

Also, we investigated the energy cost of having smart meters for electrical grid at a nation-wide scale. We proposed energy models depending on the communication technologies that are deployed in France [9].

8.2.5 End-to-end ecodesign of cloud platforms

Participants: Anne-Cécile Orgerie, Guillaume Pierre, Govind KP.

In the context of Inria's challenge on End-to-end ecodesign of cloud platforms, in collaboration with OVHCloud, we started building an system to automatically deploy data stream processing systems with their full software ecosystem in a cloud environment. The system uses software energy probes which can attribute the measured energy consumption to fine-grained elements such as the underlying cloud infrastructure, the different software elements, etc. A publication on this topic is currently in preparation.

8.3 Securing Clouds

8.3.1 Toward stealth analysis of distributed applications

Participants: Léo Cosseron, Martin Quinson, Louis Rilling, Matthieu Simonin.

In the TANSIV project we aim at extending the usability of SimGrid to software using arbitrary network communication APIs and paradigms. For instance this enables SimGrid to run distributed services implemented in operating systems kernels, such as distributed file systems, and high performance network applications based on poll-mode network interface card drivers like in the DPDK framework. To this end we proposed to interconnect SimGrid with Virtual Machine Monitors (VMM) and let all the network packets output by the virtual machines (VM) flow through SimGrid. This proposal also enhances SimGrid with applications to security, as the interconnected VMMs can be malware analysis sandboxes. Thus SimGrid enables malware analysis sandboxes to feature scalable performance-realistic network environments in order to defeat anti-analysis techniques developed by malware authors.

In 2022 two directions were studied. First, experimentally evaluating the soundness of the network simulation provided by SimGrid in the TANSIV prototype has been continued as a background task. Potentially required evolutions of SimGrid were discussed and may be implemented if experiments with micro-benchmarks confirm the requirement.

Second, as part of the master thesis then PhD thesis work of Léo Cosseron, it has been studied two approaches to use TANSIV in hardware-virtualization-based VMMs. The two approaches rely on different hardware features and were implmented in a prototype based on TANSIV, Qemu and KVM. The two approaches are being comparatively and experimentally evaluated. A first paper about this work should be submitted in 2023.

8.4 Experimenting with Clouds

8.4.1 Simulating distributed IT systems

Participants: Anne-Cécile Orgerie, Martin Quinson.

Our team plays a major role in the advance of the SimGrid simulator of IT systems. This framework has a major impact on the community. Cited by over 900 papers (60 PhD thesis, 150 journal articles, and 300 conference articles), it was used as a scientific instrument by thousands of publications over the years.

This year, the work on the framework did not lead to any new publication but instead we pursued our effort on the technical framework to prepare future scientific endeavors. We worked to ensure that it correctly captures the concepts needed by the experimenters, in preparation to a post-doctoral work on the simulation of the computing infrastructure behind the SKA (Square Kilometer Array telescope) scientific infrastructure starting in January 2023.

Our work on SimGrid is fully integrated into the other research efforts of the Myriads team. This year our main contribution on this topic was a new performance model of the Wi-Fi networks that is now integrated to the framework [6]. This enables the study of these networks within the simulator. Along the same line, the work on the TANSIV project described in previous section also required some adaptation to the simulator, to further increase the prediction accuracy when exchanging small data packets on local area networks.

8.4.2 Tools for experimentation

Participants: Matthieu Simonin.

In collaboration with the STACK team and in the context of the Discovery IPL, novel experimentation tools have been developed. In this context experimenting with large software stacks (OpenStack, Kubernetes) was required. These stacks are often tedious to handle. However, practitioners need a right abstraction level to express the moving nature of experimental targets. This includes being able to easily change the experimental conditions (e.g underlying hardware and network) but also the software configuration of the targeted system (e.g service placement, fined-grained configuration tuning) and the scale of the experiment (e.g migrate the experiment from one small testbed to another bigger testbed).

In this spirit we discuss in [23] a possible solution to the above desiderata.

The outcome is a library (EnOSlib) target reusability in experiment driven research in distributed systems.

The tool is used in several articles (see here). In particular, in [24] the tool is used to build an ad hoc framework for studying FOG applications.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Défi Inria OVHcloud (2021-2025)

Participants: Anne-Cécile Orgerie, Shadi Ibrahim, Guillaume Pierre.

The goal of this collaborative framework between the OVHcloud and Inria is to explore new solutions for the design of cloud computing services that are more energy-efficient and environment friendly. Five Inria project-teams are involved in this challenge including Avalon, Inocs, Myriads, Spirals, Stack.

Members of the Myraids team will contribute to four sub-challenges including (1) Software ecodesign of a data stream processing service; (2) energy-efficient data management; (3) observation of bare metal co-location platforms and proposal of energy reduction catalogues and models; and (4) modelling and designing a framework and its environmental Gantt Chart to manage physical and logical levers.

Défi Inria Hive (2022-2026)

Participants: Shadi Ibrahim, Guillaume Pierre.

The goal of this collaborative framework between Hive and Inria is to explore new solutions for the design and realization of large scale secure and reliable Peer-to-Peer Cloud storage. Four Inria project-teams are involved in this challenge including COAST, Myriads, WIDE, COATI.

Members of the Myraids team will contribute to two axes. Specifically, the Myriads team will coordinate the axis on reliable and cost-efficient data placement and repair in P2P storage over immutable data; and contribute to the axis on the management of mutable data over P2P storage. The actual work is expected to start in 2023.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

Hermes

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

Duration: 2019 - 2022

Coordinator: Shadi Ibrahim

Partners:

- Lawrence Berkeley National Laboratory Berkeley (États-Unis)

Partner Coordinator: Suren Byna (sbyna@lbl.gov)

Inria contact: Shadi Ibrahim

Summary: 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.

10.1.2 Inria associate team not involved in an IIL or an international program

FogRein

Title: Steering Efficiency for Distributed Applications

Duration: 2019 - 2022

Coordinator: Martin Quinson

Partners:

- Northeastern University Boston (États-Unis)

Partner Coordinator: Gene Cooperman (G.Cooperman@northeastern.edu)

Inria contact: Martin Quinson

Summary: In Fog Computing, the Internet of Things (IoT), and Intermittent Computing, low-power devices migrate geographically, and are required to rapidly assimilate new data in a power-efficient manner. This is a key component of any Smart Interfaces solution as devices migrate from the IT infrastructure to the Edge of the Cloud in order to provide Function-as-a-Service, High-availability mobility, and IT infrastructure malleability. A three-tier strategy is proposed toward steering Fog applications in order to optimize the energy efficiency and sustainability. The strategy will leverage the backgrounds of the participants in Fog Computing, checkpointing, scheduling, Green Levers within the IT infrastructure, and a simulation infrastructure for predicting and efficiently steering such distributed applications. The Inria team and the Northeastern team are uniquely positioned to make rapid progress due to their long history of collaborative research based on visits by both permanent members and PhD students in the two directions.

10.2 International research visitors

10.2.1 Visits of international scientists

Other international visits to the team

Gene Cooperman

Status (Professor)

Institution of origin: College of Computer and Information Science, Northeastern University

Country: United States

Dates: From May 31 to June 18, 2022

Context of the visit: Discuss the obtained results and future directions in the context of the FogRein associate team and the ANR KerStream project.

Mobility program/type of mobility: research stay

Radita Liem

Status (PhD student)

Institution of origin: RWTH AACHEN University

Country: Germany

Dates: Apr 2022 until Nov 2022

Context of the visit: Work on data partitioning in data workflows in teh context of the ANR KerStream project.

Mobility program/type of mobility: research stay

10.3 European initiatives

10.3.1 H2020 projects

Fed4FIREplus Fed4FIREplus project on cordis.europa.eu

Title: Federation for FIRE Plus

Duration: From January 1, 2017 to June 30, 2022

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- UNIVERSITE DE LORRAINE (UL), France
- ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS (CENTRE FOR RESEARCH AND TECHNOLOGY HELLAS CERTH), Greece
- THE PROVOST, FELLOWS, FOUNDATION SCHOLARS AND THE OTHER MEMBERS OF BOARD, OF THE COLLEGE OF THE HOLY & UNDIVIDED TRINITY OF QUEEN ELIZABETH NEAR DUBLIN (TRINITY COLLEGE DUBLIN), Ireland
- INSTITUT JOZEF STEFAN (JSI), Slovenia
- MARTEL INNOVATE BV, Netherlands
- ETHNICON METSOVION POLYTECHNION (NATIONAL TECHNICAL UNIVERSITY OF ATHENS - NTUA), Greece
- FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV (FHG), Germany
- INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM (IMEC), Belgium
- GEANT VERENIGING (GEANT VERENIGING), Netherlands
- NORDUNET A/S (NORDUNET A/S), Denmark
- INSTYTUT CHEMII BIOORGANICZNEJ POLSKIEJ AKADEMII NAUK, Poland
- TECHNISCHE UNIVERSITAT BERLIN (TUB), Germany
- ATOS SPAIN SA, Spain
- MANDAT INTERNATIONAL ALIAS FONDATION POUR LA COOPERATION INTERNATIONALE (MI), Switzerland
- UNIVERSITY OF SOUTHAMPTON (SOUTHAMPTON), United Kingdom
- EURESCOM-EUROPEAN INSTITUTE FOR RESEARCH AND STRATEGIC STUDIES IN TELECOMMUNICATIONS GMBH (EURESCOM), Germany
- UNIVERSIDAD DE CANTABRIA (UC), Spain
- ATOS CONSULTING CANARIAS SA UNIPERSONAL, Spain
- UNIVERSIDAD DE MALAGA (UMA), Spain
- GEANT LIMITED (GEANT LIMITED), United Kingdom
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (CNRS), France
- FUNDACIO PRIVADA I2CAT, INTERNET I INNOVACIO DIGITAL A CATALUNYA (CERCA - i2CAT), Spain
- MARTEL GMBH (MARTEL GMBH), Switzerland
- UNIVERSITEIT VAN AMSTERDAM (UvA), Netherlands
- SORBONNE UNIVERSITE, France

Inria contact: David Margery

Coordinator:

Summary: The Fed4FIRE+ project has the objective to run and further improve Fed4FIRE's "best-in-town" federation of experimentation facilities for the Future Internet Research and Experimentation initiative. Federating a heterogeneous set of facilities covering technologies ranging from wireless, wired, cloud services and open flow, and making them accessible through common frameworks and tools suddenly opens new possibilities, supporting a broad range of experimenter communities covering a wide variety of Internet infrastructures, services and applications.

Fed4FIRE+ will continuously upgrade and improve the facilities and include technical innovations, focused towards increased user satisfaction (user-friendly tools, privacy-oriented data management, testbed SLA and reputation, experiment reproducibility, service-level experiment orchestration, federation ontologies, etc.). It will open this federation to the whole FIRE community and beyond, for experimentation by industry and research organisations, through the organization of Open Calls and Open Access mechanisms

The project will also establish a flexible, demand-driven framework which allows test facilities to join during the course of its lifetime by defining a set of entry requirements for new facilities to join and to comply with the federation.

FIRE Experimental Facilities generate an ever increasing amount of research data that provides the foundation for new knowledge and insight into the behaviour of FI systems. Fed4FIRE+ will participate in the Pilot on Open Research Data in Horizon 2020 to offer open access to its scientific results, to the relevant scientific data and to data generated throughout the project's lifetime.

Fed4FIRE+ will finally build on the existing community of experimenters, testbeds and tool developers and bring them together regularly (two times a year) in engineering conferences to have maximal interaction between the different stakeholders involved.

10.4 National initiatives

ANR KerStream (2017-2022)

Participants: Shadi Ibrahim.

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

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.

ANR FACTO (2021-2024)

Participants: Anne-Cécile Orgerie, Martin Quinson, François Lemercier.

The number of smart homes is rapidly expanding worldwide with an increasing amount of wireless IT devices. The diversity of these devices is accompanied by the development of multiple wireless protocols and technologies that aim to connect them. However, these technologies offer overlapping capabilities. This overprovisioning is highly suboptimal from an energy point of view and can be viewed as a first barrier towards sustainable smart homes. Therefore, in the FACTO project, we propose to design a multi-purpose network based on a single optimized technology (namely Wi-Fi), in order to offer an energy-efficient, adaptable and integrated connectivity to all smart home's devices.

ANR Dark-Era (2021-2025)

Participants: Martin Quinson.

The future Square Kilometer Array (SKA) radio telescope poses unprecedented challenges to the underlying computational system. The instrument is expected to produce a sustained rate of Terabytes of data per second, mandating on-site pre-processing to reduce the size of data to be transferred. However, the electromagnetic noise of a traditional computing center would hinder the quality of the measurements if located near to the instrument. As a result, the Science Data Processor (SDP) pipeline will only have an energy budget of only 1 MWatt to execute a complex algorithm chain estimated at 250 Petaops/s. Because of these requirements, the SDP must be an innovative data-oriented infrastructure running on a disaggregated architecture combining standard HPC systems with dedicated accelerators such as GPU or FPGA.

The goal of the DarkEra project is to contribute to the performance assessment both in time and energy of new complex scientific algorithms on not-yet-existing complex computing infrastructures. To that extend, a prototyping tool will be developed for the prospective profiling of data-oriented applications during their development.

10.5 Regional initiatives

ARED TDFDE (2022-2025)

Participants: Khaled Arsalane, Guillaume Pierre.

The PhD thesis of Khaled Arsalane is funded at 50% by the TDFDE project under the ARED program of Région Bretagne. This project investigates performance modeling and optimization of agregation operators within geo-distributed data stream processing platforms.

ARED TANSIV (2022-2025)

Participants: Léo Cosseron, Martin Quinson, Louis Rilling, Matthieu Simonin.

The PhD thesis of Léo Cosseron is funded at 50% by the ARED program "Breizh Cyber Valley" of Région Bretagne and 50% by the Creach Labs. This project studies how to defeat malware evasion techniques based on network performance analysis by adding a virtual realistic networks to analysis environments.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

Member of the organizing committees

- Shadi Ibrahim was publicity co-chair for the 34th IEEE International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD 2022), 2022,Bordeaux, Nouvelle-Aquitaine, France.
- Guillaume Pierre was the finance chair of the ACM European Conference on Computer Systems (EuroSys), Rennes, France.
- François Lemercier was a member of the organizing committee of the "Journées du GDR RSD" 27th and 28th of april, 2022, Rennes, France.

11.1.2 Scientific events: selection

Chair of conference program committees

- Shadi Ibrahim was track co-chair for the Software track of the 51st International Conference on Parallel Processing (ICPP 2022).
- Shadi Ibrahim was a program vice chair for 2022 IEEE International Conference on Digital Twin (DigitalTwin 2022).
- Anne-Cécile Orgerie was vice-chair of the PhD Forum for IEEE International Parallel & Distributed Processing Symposium (IPDPS 2022).

Member of the conference program committees

- Shadi Ibrahim was a member of the program committees of SC 2022 (Research papers and research posters), IEEE IPDPS 2022, IEEE Cluster 2022, IEEE/ACM CCGrid 2022, IEEE HiPC 2022, ACM ApSys 2022, IEEE/ACM PDSW@SC 2022, ACM CHEOPS@Eurosys 2022.
- Anne-Cécile Orgerie was a member of the program committees of IEEE IPDPS 2022, IEEE/ACM CCGrid 2022, ICCCN 2022 and ICPP 2022.
- Guillaume Pierre was a member of the program committees of TheWebConf 2022, IEEE/ACM CCGrid 2022, ICFEC 2022, IEEE IC2E 2022, IEEE JCC 2022, and MiddleWedge 2022
- Nikos Parlavantzas was a member of the program committees of IEEE/ACM UCC 2022, IEEE CloudCom 2022, IEEE ISPDC 2022, and VHPC'22
- Cédric Tedeschi was a member of the program committee of the 51st International Conference on Parallel Processing (ICPP 2022)

Reviewer

- François Lemercier was a reviewer for the 25th Conference on Innovation in Clouds, Internet and Networks and Workshops (ICIN 22).

11.1.3 Journal

Member of the editorial boards

- Shadi Ibrahim is an associate editor of IEEE Internet Computing Magazine.
- Shadi Ibrahim is a young associate editor of the Springer Frontiers of Computer Science journal.
- Anne-Cécile Orgerie is a member of the editorial board of IEEE Transactions on Parallel and Distributed Systems.

Reviewer - reviewing activities

- Shadi Ibrahim was a reviewer for IEEE Computer, IEEE Transactions on Industrial Informatics, Springer Parallel Computing Journal, and Springer Future Generation Computer Systems.
- Marin Bertier was a reviewer for Journal of Supercomputing.
- Nikos Parlavantzas was a reviewer for the IEEE Transactions on Cloud Computing.

11.1.4 Invited talks

- Shadi Ibrahim: "Time to Revisit Erasure Codes in Data-intensive Clusters". The 6th edition of the Performance and Scalability of Storage Systems workshop (Per3S), Institut Mines Telecom Palaiseau, June 13th, 2022.
- Anne-Cécile Orgerie: “Sustainability of distributed systems”, keynote at IEEE SiPS (IEEE Workshop on Signal Processing Systems), Rennes, November 4th, 2022.
- Anne-Cécile Orgerie: “Quelques idées fausses sur la consommation énergétique des systèmes distribué”, keynote at Compas (Conférence francophone d’informatique en Parallélisme, Architecture et Système), Amiens, July 8th, 2022.
- Anne-Cécile Orgerie: “Réduire la consommation énergétique des centres de données”, keynote at MaDICS Symposium (Masses de Données, Informations et Connaissances en Sciences), Lyon, July 12th, 2022.
- Anne-Cécile Orgerie: “Measuring the energy consumption of Clouds”, Seminar at LaBRI, Bordeaux, November 30th, 2022.
- Anne-Cécile Orgerie: “Energy consumption and environmental impacts of distributed systems”, seminar at Polaris Colloquium of CRIStAL, Lille, October 20th, 2022.
- Anne-Cécile Orgerie: “Energy consumption and environmental impacts of data centers”, seminar at LIRIS, Lyon, September 13th, 2022.
- Anne-Cécile Orgerie: “Consommation énergétique et impacts environnementaux du numérique”, Seminar at ISCR (Institut des Sciences Chimiques de Rennes), Rennes, June 30th, 2022.
- Anne-Cécile Orgerie: “Measuring the energy consumption and the environmental impacts of ICT”, Seminar at OSUR (Observatoire des Sciences de l’Univers), Rennes, April 11th, 2022.

11.1.5 Leadership within the scientific community

- Anne-Cécile Orgerie is director of the CNRS service group on ICT environmental impact (GDS EcoInfo).
- Anne-Cécile Orgerie is chief scientist for the Rennes site of Grid’5000.
- Guillaume Pierre is a member of the ACM Middleware conference’s steering committee.
- Shadi Ibrahim is a member of the steering committee of the International Parallel Data Systems Workshop.

11.1.6 Scientific expertise

- Anne-Cécile Orgerie was a member of the selection committees for an assistant professor position at Université Toulouse 3 and Inria research scientist positions (CRCN and ISFP) at the Rennes site in 2022.
- Guillaume Pierre was the chair of the selection committee for an assistant professor position at Université de Rennes 1, and a reviewer for three candidates at Université de Nantes who applied for a promotion to full professor positions.
- Cédric Tedeschi was a member of the selection committee for an assistant professor position at Université de Bretagne Occidentale and a member of the selection committee for an assistant professor position at Université Savoie Mont-Blanc in 2022.

11.1.7 Research administration

- Anne-Cécile Orgerie is an officer (chargée de mission) for the IRISA cross-cutting axis on Green IT.
- Anne-Cécile Orgerie is member of the Inria Evaluation Committee.
- Anne-Cécile Orgerie is member of the steering committee of the CNRS GDR RSD.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Bachelor: Marin Bertier, Networks, Département Informatique L3, Insa Rennes.
- Bachelor: Marin Bertier, C Language Département Informatique L3, Insa Rennes.
- Bachelor: Marin Bertier, C Language, Département Mathématique L3, Insa Rennes.
- Bachelor: Nikos Parlavantzas, Theoretical and practical study, Département Informatique L3, Insa Rennes.
- Bachelor: Nikos Parlavantzas, Networks, Département Informatique L3, Insa Rennes.
- Bachelor: Nikos Parlavantzas, Multi-core architectures, Département Informatique L3, Insa Rennes.
- Bachelor: Jean-Louis Pazat, Introduction to programming L1, Département STPI, INSA de Rennes.
- Bachelor: Jean-Louis Pazat, High Performance Computing, Département Informatique L3, Insa Rennes.
- Bachelor: Jean-Louis Pazat, High Performance Computing, Département Mathematiques L3, Insa Rennes.
- Bachelor: Guillaume Pierre, Systèmes Informatiques, L3 MIAGE, Univ. Rennes 1.
- Bachelor: Guillaume Pierre, Systèmes d'exploitation, L3 Informatique, Univ. Rennes 1.
- Bachelor: Martin Quinson, Architecture et Systèmes, 60 hETD, L3 Informatique, ENS Rennes.
- Bachelor: Martin Quinson, Pedagogy, 15 hETD, L3 Informatique, ENS Rennes.
- Bachelor: Cédric Tedeschi, Cloud and networks, L3, Univ. Rennes 1.
- Master: Marin Bertier, Operating Systems, Département Informatique M1, INSA de Rennes
- Master: Marin Bertier, Distributed systems, Département Informatique M2, INSA de Rennes
- Master: Anne-Cécile Orgerie, Green ICT, 4.5 hETD, M2, Telecom SudParis Evry.
- Master: Anne-Cécile Orgerie, Green ICT, 3 hETD, M2, Telecom Paris.
- Master: Anne-Cécile Orgerie, Green IT, 6 hETD, M1, INSA Rennes.
- Master: Nikos Parlavantzas, Clouds, M1, INSA Rennes.
- Master: Nikos Parlavantzas, Performance Evaluation, M1, INSA Rennes.
- Master: Nikos Parlavantzas, Operating Systems, M1, INSA Rennes.
- Master: Nikos Parlavantzas, Parallel programming, M1, INSA Rennes.
- Master: Nikos Parlavantzas, Big Data Storage and Processing, M2, INSA Rennes.
- Master: Nikos Parlavantzas, NoSQL, M2, Statistics for Smart Data, ENSAI, Bruz.

- Master: Nikos Parlavantzas, 4th-year Project, M1, INSA Rennes.
- Master: Jean-Louis Pazat, Parallel Computing, M1 Département Informatique Insa Rennes.
- Master: Jean-Louis Pazat, Internet Of Things, M1 & M2 Département Informatique Insa Rennes.
- Master: Guillaume Pierre, Distributed Systems, M1, Univ. Rennes 1.
- Master: Guillaume Pierre, Service technology, M1, Univ. Rennes 1.
- Master: Guillaume Pierre, Advanced Cloud Infrastructures, M2, Univ. Rennes 1.
- Master: Martin Quinson, C++ system programming (20h ETD), ENS Rennes.
- Master: Martin Quinson, Préparation à l'Agrégation d'Informatique (Networking, 20h ETD), ENS Rennes.
- Master: Martin Quinson, Scientific Outreach, M2, 30 hEDT, ENS Rennes.
- Master: Cédric Tedeschi, Concurrency in Systems and Networks, M1, Univ. Rennes 1.
- Master: Cédric Tedeschi, Service Technology, M1, Univ. Rennes 1.
- Master: Cédric Tedeschi, Parallel Programming, M1, Univ. Rennes 1.
- Master: Cédric Tedeschi, Advanced Cloud Infrastructures, M2, Univ. Rennes 1.
- Master: Shadi Ibrahim, Cloud Computing and Hadoop Technologies, 36hETD, M2 : Statistics for Smart Data, ENSAI, Bruz.
- Master: Shadi Ibrahim, Smart City Services: From applications to Infrastructures (SCS), 18hETD, M2 , Univ. Rennes 1.
- Master: Shadi Ibrahim, Cloud and Big data, 15hETD, M1, ENS Rennes, Bruz.
- Master: Shadi Ibrahim, Distributed Big Data, 36hETD, M2, ENSAI, Bruz.
- Master: François Lemercier, Networking, Services and Protocols, M1, Univ. Rennes 1.
- Master: François Lemercier, Service Technology, M1, Univ. Rennes 1.
- Master: François Lemercier, Software Engineering Project, M1, Univ. Rennes 1.

11.2.2 Supervision

- PhD in progress: Clément Courageux-Sudan, "Reducing the energy consumption of Internet of Things", started in October 2020, supervised by Anne-Cécile Orgerie and Martin Quinson.
- PhD in progress: Adrien Gougeon, "Designing an energy-efficient communication network for the dynamic and distributed control of the electrical grid", started in September 2019, supervised by Anne-Cécile Orgerie and Martin Quinson (defense on January 11th 2023).
- PhD in progress: Emmanuel Gnibga, "Modeling and optimizing edge computing infrastructures and their electrical system", started in November 2021, supervised by Anne-Cécile Orgerie and Anne Blavette.
- PhD in progress: Vladimir Ostapenco, Modeling and design of a framework and its Gantt Chart to manage physical and logical environmental levers, started in December 2021, supervised by Laurent Lefèvre and Anne-Cécile Orgerie.
- PhD in progress: Maxime Agusti, Observation of baremetal co-location platforms, models and catalog proposal to reduce energy consumption, started in December 2021, supervised by Eddy Caron, Laurent Lefèvre and Anne-Cécile Orgerie.

- PhD in progress: Chih-Kai Huang, "scalable decentralized fog commputing platforms", started in 2021, supervised by Guillaume Pierre.
- PhD in progress: Khaled Arsalane, "performance modeling of agregation operators in geo-distributed data stream processing systems", started in October 2022, supervised by Guillaume Pierre.
- PhD in progress: Davaadorj Battulga, "Stream Processing Pipelines in Fog Environment", started in September 2018, supervised by Cédric Tedeschi and Daniele Miorandi.
- PhD in progress: Volodia Parol-Guarino, "Flexible resource allocation for FaaS applications in the fog", started in October 2022, supervised by Nikos Parlavantzas.

11.2.3 Juries

- Anne-Cécile Orgerie was a member of the PhD defense of June Sallou (Université Rennes 1), February 23rd 2022.
- Anne-Cécile Orgerie was a member of the PhD defense of Ali Hamdan (Université Grenoble Alpes), March 21st 2022.
- Anne-Cécile Orgerie was a member of the PhD defense of Pedro Victor Borges Caldas Da Silva (Telecom SudParis), December 12th 2022.
- Anne-Cécile Orgerie was chairperson of the PhD defense of Paulo Ricardo Rodrigues De Souza Junior, November 23rd 2022.
- Guillaume Pierre was chairperson of the PhD defense of Fabien Coulon (Université de Rennes 1), March 3rd 2022.
- Guillaume Pierre was a reviewer at the PhD defense of Fabiana Rossi (University Roma Tor-Vergata), April 13th 2022.
- Guillaume Pierre was chairperson of the PhD defense of Bruno Stevant (INSA Rennes), May 23rd 2022.
- Guillaume Pierre was chairperson of the PhD defense of Yasmina Bouizem (Université Rennes 1), June 8th 2022.
- Cédric Tedeschi was a reviewer of the PhD defense of Patient Ntumba (Sorbonne université), Septenber 9th 2022

11.3 Popularization

11.3.1 Internal or external Inria responsibilities

- Shadi Ibrahim is co-organizing SCI-Rennes seminar: a monthly scientific seminars for all staff at Inria research centre at Rennes University.

11.3.2 Articles and contents

- Anne-Cécile Orgerie co-authored the article “Le vrai coût énergétique du numérique” with Laurent Lefèvre (Avalon team) in Interstices in October 2022.

11.3.3 Education

- “L codent L créent” is an outreach program to send PhD students to teach Python to middle school students in 8 sessions of 45 minutes. Tassadit Bouadi (Lacodam), Camille Maumet (Empenn) and Anne-Cécile Orgerie (Myriads) are coordinating the local version of this program, initiated in Lille. The first session in Rennes occured in April 2019, and a new session (the 5th) has started for 2023. The program is currently supported by: Fondation Blaise Pascal, ED MathSTIC, ENS de Rennes, Université Rennes 1 and Fondation Rennes 1.

11.3.4 Interventions

- Anne-Cécile Orgerie was the speaker of the *Mardi de l'Espace des Sciences* in Rennes on February 9th 2022.

12 Scientific production

12.1 Major publications

[1] H. Casanova, A. Legrand, M. Quinson and F. Suter. 'SMPI Courseware: Teaching Distributed-Memory Computing with MPI in Simulation'. In: *EduHPC-18 - Workshop on Education for High-Performance Computing*. Dallas, United States, Nov. 2018, pp. 1–10. URL: https://hal.inria.fr/hal-01891513.

12.2 Publications of the year

International journals

[2] E. Ahvar, A.-C. Orgerie and A. Lebre. 'Estimating Energy Consumption of Cloud, Fog and Edge Computing Infrastructures'. In: *IEEE Transactions on Sustainable Computing* 7.2 (Apr. 2022), pp. 277–288. DOI: 10.1109/TSUSC.2019.2905900. URL: https://hal.archives-ouvertes.fr/hal-02083080.

[3] A. Guermouche and A.-C. Orgerie. 'Thermal design power and vectorized instructions behavior'. In: *Concurrency and Computation: Practice and Experience* 34.2 (Jan. 2022), pp. 1–18. DOI: 10.1002/cpe.6261. URL: https://hal.archives-ouvertes.fr/hal-03185821.

[4] K. Toczé, A. J. Fahs, G. Pierre and S. Nadjm-Tehrani. 'VioLinn: Proximity-aware Edge Placement with Dynamic and Elastic Resource Provisioning'. In: *ACM Transactions on Internet of Things* (2022), pp. 1–30. DOI: 10.1145/3573125. URL: https://hal.inria.fr/hal-03869221.

International peer-reviewed conferences

[5] D. Battulga, M. Farhadi, M. A. Tamiru, L. Wu and G. Pierre. 'LivingFog: Leveraging fog computing and LoRaWAN technologies for smart marina management (experience paper)'. In: ICIN 2022 - 25th Conference on Innovation in Clouds, Internet and Networks. Paris, France, 7th Mar. 2022, pp. 1–8. URL: https://hal.inria.fr/hal-03531372.

[6] C. Courageux-Sudan, L. Guegan, A.-C. Orgerie and M. Quinson. 'A Flow-Level Wi-Fi Model for Large Scale Network Simulation'. In: MSWiM 2022 - International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. MSWiM 2022 - International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. Montreal, Canada, Oct. 2022. DOI: 10.1145/3551659.3559022. URL: https://hal.science/hal-03777726.

[7] J. Darrous and S. Ibrahim. 'Understanding the Performance of Erasure Codes in Hadoop Distributed File System'. In: CHEOPS 22 - Proceedings of the Workshop on Challenges and Opportunities of Efficient and Performant Storage Systems. Rennes, France: ACM, 5th Apr. 2022, pp. 24–32. DOI: 10.1145/3503646.3524296. URL: https://hal.inria.fr/hal-03890398.

[8] A. Gougeon, F. Lemercier, A. Blavette and A.-C. Orgerie. 'Influence of Communication Technologies in Smart Grid Power Congestion Management'. In: GreenCom-2022 - 18th IEEE International Conference on Green Computing and Communications. Espoo, Finland, Aug. 2022, pp. 1–10. URL: https://hal.archives-ouvertes.fr/hal-03711670.

[9] A. Gougeon, F. Lemercier, A. Blavette and A.-C. Orgerie. 'Modeling the End-to-End Energy Consumption of a Nation-Wide Smart Metering Infrastructure'. In: ISCC 2022 - IEEE Symposium on Computers and Communications. ISCC 2022 - IEEE Symposium on Computers and Communications. Rhodes, Greece: IEEE, June 2022, pp. 1–7. URL: https://hal.archives-ouvertes.fr/hal-03666587.

[10] C.-K. Huang and G. Pierre. 'Acala: Aggregate Monitoring for Geo-Distributed Cluster Federations'. In: SAC 2023 - 38th ACM/SIGAPP Symposium On Applied Computing. Tallinn, Estonia, 27th Mar. 2023. URL: https://hal.inria.fr/hal-03899133.

[11] T. Lambert, S. Ibrahim, T. Jain and D. Guyon. 'Stragglers' Detection in Big Data Analytic Systems: The Impact of Heartbeat Arrival'. In: CCGrid 2022 - 22nd International Symposium on Cluster, Cloud and Internet Computing. Taormina, Italy: IEEE, 16th May 2022, pp. 747–751. DOI: 10.1109/CCGrid54584.2022.00084. URL: https://hal.inria.fr/hal-03777656.

[12] P. Souza Junior, D. Miorandi and G. Pierre. 'Good Shepherds Care For Their Cattle: Seamless Pod Migration in Geo-Distributed Kubernetes'. In: ICFEC 2022 - 6th IEEE International Conference on Fog and Edge Computing. Taormina, Italy: IEEE, 16th May 2022, pp. 1–9. URL: https://hal.inria.fr/hal-03587358.

[13] S. Wu, Z. Huang, P. Chen, H. Fan, S. Ibrahim and H. Jin. 'Container-aware I/O stack: bridging the gap between container storage drivers and solid state devices'. In: VEE '22 - 18th ACM SIGPLAN/SIGOPS International Conference on Virtual Execution Environments. Virtual, Swaziland: ACM, 1st Mar. 2022, pp. 18–30. DOI: 10.1145/3516807.3516818. URL: https://hal.inria.fr/hal-03890424.

[14] A. C. Zhou, R. Qiu, T. Lambert, T. Allard, S. Ibrahim and A. El Abbadi. 'PGPregel: An End-to-End System for Privacy-Preserving Graph Processing in Geo-Distributed Data Centers'. In: *Proceedings of the 13th Symposium on Cloud Computing*. SoCC '22: ACM Symposium on Cloud Computing. San Francisco California, United States: ACM, 7th Nov. 2022, pp. 386–402. DOI: 10.1145/3542929.3563474. URL: https://hal.archives-ouvertes.fr/hal-03879423.

Conferences without proceedings

[15] R. Liem and S. Ibrahim. 'Revisit Data Partitioning in Data-intensive workflows'. In: PDSW 2022 - 7th International Parallel Data Systems Workshop. Dallas, United States, 14th Nov. 2022. URL: https://hal.inria.fr/hal-03913369.

[16] A. Voyez, T. Allard, G. Avoine, P. Cauchois, E. Fromont and M. Simonin. 'Membership Inference Attacks on Aggregated Time Series with Linear Programming'. In: SECRYPT 2022 - 19th International Conference on Security and Cryptography. Lisbon, France: SCITEPRESS - Science and Technology Publications, 11th July 2022, pp. 193–204. DOI: 10.5220/0011276100003283. URL: https://hal.archives-ouvertes.fr/hal-03726234.

Doctoral dissertations and habilitation theses

[17] Y. Bouizem. 'Fault tolerance in FaaS environments'. Université Rennes 1, 8th May 2022. URL: https://theses.hal.science/tel-03882666.

[18] P. Souza Junior. 'Stateful Application Migration in Geo-Distributed Systems'. Université de Rennes 1, 23rd Nov. 2022. URL: https://hal.inria.fr/tel-03875710.

Reports & preprints

[19] Y. Bouizem, D. Dib, N. Parlavantzas, C. Morin and F. Lahfa. *Request Replication for FaaS Fault Tolerance*. RR-9444. Inria, 4th Jan. 2022, pp. 1–19. URL: https://hal.inria.fr/hal-03510322.

[20] P. Ciblat, J. Combaz, M. Coupechoux, K. Marquet and A.-C. Orgerie. *Impacts environnementaux de la 5G: Partie 1 : La technologie 5G*. EcoInfo, 11th Oct. 2022, pp. 1–12. URL: https://hal.archives-ouvertes.fr/hal-03810501.

[21] A. Voyez, T. Allard, G. Avoine, P. Cauchois, E. Fromont and M. Simonin. *Unique in the Smart Grid -The Privacy Cost of Fine-Grained Electrical Consumption Data*. 9th Nov. 2022. URL: https://hal.archives-ouvertes.fr/hal-03833605.

12.3 Other

Scientific popularization

[22] A.-C. Orgerie and L. Lefèvre. 'Le vrai coût énergétique du numérique'. In: *Interstices* (10th July 2022). URL: https://hal.inria.fr/hal-03889053.

12.4 Cited publications

[23] R.-A. Cherrueau, M. Simonin and A. Van Kempen. 'EnosStack: A LAMP-like stack for the experimenter'. In: *INFOCOM WKSHPS 2018 - IEEE International Conference on Computer Communications*. Honolulu, United States: IEEE, Apr. 2018, pp. 336–341. DOI: 10.1109/INFCOMW.2018.8407024. URL: https://hal.inria.fr/hal-01916484.

[24] D. Rosendo, P. Silva, M. Simonin, A. Costan and G. Antoniu. 'E2Clab: Exploring the Computing Continuum through Repeatable, Replicable and Reproducible Edge-to-Cloud Experiments'. In: *Cluster 2020 - IEEE International Conference on Cluster Computing*. Kobe, Japan, Sept. 2020, pp. 1–11. DOI: 10.1109/CLUSTER49012.2020.00028. URL: https://hal.archives-ouvertes.fr/hal-02916032.