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DISTRIBUTED SYSTEMS AND SERVICES

DISTRIBUTED SYSTEMS AND MIDDLEWARE

DISTRIBUTED AND HIGH PERFORMANCE COMPUTING

DISTRIBUTED PROGRAMMING AND SOFTWARE ENGINEERING

NETWORKS AND TELECOMMUNICATIONS

ACES Project-Team

3. Research Program

3.1. Programming Context

The goal of ambient computing is to seamlessly merge virtual and real environments. A real environment is composed of objects from the physical world, e.g., people, places, machines. A virtual environment is any information system, e.g., the Web. The integration of these environments must permit people and their information systems to implicitly interact with their surrounding environment.

Ambient computing applications are able to evaluate the state of the real world through sensing technologies. This information can include the position of a person (caught with a localization system like GPS), the weather (captured using specialized sensors), etc. Sensing technologies enable applications to automatically update digital information about events or entities in the physical world. Further, interfaces can be used to act on the physical world based on information processed in the digital environment. For example, the windows of a car can be automatically closed when it is raining.

This real-world and virtual-world integration must permit people to implicitly interact with their surrounding environment. This means that manual device manipulation must be minimal since this constrains person mobility. In any case, the relative small size of personal devices can make them awkward to manipulate. In the near future, interaction must be possible without people being aware of the presence of neighbouring processors.

Information systems require tools to *capture* data in its physical environment, and then to *interpret*, or process, this data. A context denotes all information that is pertinent to a person-centric application. There are three classes of context information:

- The *digital context* defines all parameters related to the hardware and software configuration of the device. Examples include the presence (or absence) of a network, the available bandwidth, the connected peripherals (printer, screen), storage capacity, CPU power, available executables, etc.
- The *personal context* defines all parameters related to the identity, preferences and location of the person who owns the device. This context is important for deciding the type of information that a personal device needs to acquire at any given moment.
- The *physical context* relates to the person's environment; this includes climatic condition, noise level, luminosity, as well as date and time.

All three forms of context are fundamental to person-centric computing. Consider for instance a virtual museum guide service that is offered via a PDA. Each visitor has his own PDA that permits him to receive and visualise information about surrounding artworks. In this application, the *pertinent* context of the person is made up of the artworks situated near the person, the artworks that interest him as well as the degree of specialisation of the information, i.e., if the person is an art expert, he will desire more detail than the occasional museum visitor.

There are two approaches to organising data in a real to virtual world mapping: a so-called *logical* approach and a *physical* approach. The logical approach is the traditional way, and involves storing all data relevant to the physical world on a service platform such as a centralised database. Context information is sent to a person in response to a request containing the person's location co-ordinates and preferences. In the example of the virtual museum guide, a person's device transmits its location to the server, which replies with descriptions of neighbouring artworks.

The main drawbacks of this approach are scalability and complexity. Scalability is a problem since we are evolving towards a world with billions of embedded devices; complexity is a problem since the majority of physical objects are unrelated, and no management body can cater for the integration of their data into a service platform. Further, the model of the physical world must be up to date, so the more dynamic a system, the more updates are needed. The services platform quickly becomes a potential bottleneck if it must deliver services to all people.

The physical approach does not rely on a digital model of the physical world. The service is computed wherever the person is located. This is done by spreading data onto the devices in the physical environment; there are a sufficient number of embedded systems with wireless transceivers around to support this approach. Each device manages and stores the data of its associated object. In this way, data are physically linked to objects, and there is no need to update a positional database when physical objects move since the data *physically* moves with them.

With the physical approach, computations are done on the personal and available embedded devices. Devices interact when they are within communication range. The interactions constitute delivery of service to the person. Returning to the museum example, data is directly embedded in a painting's frame. When the visitor's guide meets (connects) to a painting's devices, it receives the information about the painting and displays it.

3.2. Spatial Information Systems

One of the major research efforts in ACES over the last few years has been the definition of the Spread programming model to cater for spacial context. The model is derived from the Linda [10] tuple-space model. Each information item is a *tuple*, which is a sequence of typed data items. For example, `<10, 'Peter', -3.14>` is a tuple where the first element is the integer 10, the second is the string '"Peter" and the third is the real value -3.14. Information is addressed using patterns that match one or a set of tuples present in the tuple-space. An example pattern that matches the previous tuple is `<int, 'Peter', float>`. The tuple-space model has the advantage of allowing devices that meet for the first time to exchange data since there is no notion of names or addresses.

Data items are not only addressed by their type, but also by the physical space in which they reside. The size of the space is determined by the strength of the radio signal of the device. The important difference between Spread and other tuple-space systems (e.g., Sun's JavaSpaces [9], IBM's T-Space [13]) is that when a program issues a matching request, only the tuples filling the *physical space* of the requesting program are tested for matching. Thus, though SIS (Spatial Information Systems) applications are highly distributed by nature, they only rely on localised communications; they do not require access to a global communication infrastructure. Figure 1 shows an example of a physical tuple space, made of tuples arranged in the space and occupying different spaces.

As an example of the power of this model, consider two of the applications that we have developed using it.

- *Ubi-bus* is a spatial information application whose role is to help blind and partially blind people use public transport. When taking a bus, a blind person uses his PDA to signal his intention to a device embedded in the bus stop; this device then contacts the bus on the person's behalf. This application illustrates how data is distributed over the objects of the physical world, and generally, how devices complement human means of communication.
- *Ubi-board* is a spatial information application designed for public electronic billboards. Travel hotspots like airports and major train stations have an international customer base, so bill-board announcements need to be made in several languages. In Ubi-bus, a billboard has an embedded device. When a person comes within communication range of the billboard, his device sends a request to the billboard asking it to print the message in the language of the person. In the case where several travellers are in proximity of the billboard, the board sends a translation of its information message to each person. The Ubi-board application illustrates personal context in use, i.e., the choice of natural language, and also how actions can be provoked in the physical world without explicit intervention by the person.

../../../../projets/aces/IMG/phy-tspace.png

Figure 1. Physical Tuple Space

3.3. Coupled objects

Integrity checking is an important concern in many activities, both in the real world and in the information society. The basic purpose is to verify that a set of objects, parts, components, people remains the same along some activity or process, or remains consistent against a given property (such as a part count).

In the real world, it is a common step in logistic: objects to be transported are usually checked by the sender (for their conformance to the recipient expectation), and at arrival by the recipient. When a school get a group of children to a museum, people responsible for the children will regularly check that no one is missing. Yet another common example is to check for our personal belongings when leaving a place, to avoid lost. While important, these verification are tedious, vulnerable to human errors, and often forgotten.

Because of these vulnerabilities, problems arise: E-commerce clients sometimes receive incomplete packages, valuable and important objects (notebook computers, passports etc.) get lost in airports, planes, trains, hotels, etc. with sometimes dramatic consequences.

While there are very few automatic solutions to improve the situation in the real world, integrity checking in the computing world is a basic and widely used mechanism: magnetic and optical storage devices, network communications are all using checksums and error checking code to detect information corruption, to name a few.

The emergence of ubiquitous computing and the rapid penetration of RFID devices enable similar integrity checking solutions to work for physical objects. We introduced the concept of *coupled object*, which offers simple yet powerful mechanisms to check and ensure integrity properties for set of physical objects.

Essentially, coupled objects are a set of physical objects which defines a logical group. An important feature is that the group information is self contained on the objects which allow to verify group properties, such as completeness, only with the objects. Said it another way, the physical objects can be seen as fragments of a composite object. A trivial example could be a group made of a person, his jacket, his mobile phone, his passport and his cardholder.

The important feature of the concept are its distributed, autonomous and anonymous nature: it allows the design and implementation of pervasive security applications without any database tracking or centralized information system support. This is a significant advantage of this approach given the strong privacy issues that affect pervasive computing.

ADAM Project-Team

3. Research Program

3.1. Introduction

In order to cope with our objective, we will consider software paradigms that will help us in our approach at the various levels of our life-cycle of adaptive systems, but also in the tools themselves for their composition. We will also study these paradigms in the middleware and application design in order to extend them and to have a better understanding. These extensions will be formalized as much as possible.

3.1.1. Aspect-Oriented Software Development (AOSD)

In modern software engineering, language constructs are classified according to how they recombine partial solutions for subproblems of a problem decomposition. Some constructs (*e.g.*, methods and classes) recombine partial solutions using classic hierarchical composition. Others recombine the partial solution using what is known as crosscutting (a.k.a. aspectual) composition. With crosscutting composition, two partial solutions (called aspects) are woven into each other in a way that is dictated by so-called pointcut languages. The necessity of crosscutting composition is the main motivation for the AOSD [60], [68] paradigm. The challenge will be first to study new expressive pointcut languages in order to have a better description of composition locations in adaptable software. The second objective will be to extend and to integrate new techniques of weaving at design time, but also at run time in order to compose software safely. The third objective will be to go beyond simple aspects as persistence and logging services. We plan to study complex aspects such as transactions or replication and to control their weaving in order to master the evolution of complex software.

3.1.2. Component-Based Software Engineering (CBSE)

In a post-object world [65], software components [69] are, with other artifacts such as aspects, one of the approaches that aims at overcoming the limitations of objects and providing more flexibility and dynamicity to complex applications. For that, software components present many interesting properties, such as modularity, encapsulation, and composability. Yet, many different component models and frameworks exist. A survey of the literature references more than 20 different models (including the most well-known, such as EJB [59] and CCM [58]), but the exact number is certainly closer to 30. Indeed, each new author proposes a model to address her/his own need related to a particular execution environment (from grid computing to embedded systems) or the technical services (from advanced transactions to real-time properties), which must be provided to the application components. These different component models seldom interoperate and their design and implementation are never founded on a common ground. The research challenge that we identify is to define and implement solutions for adaptive software components. These components will be adaptive in the sense that they will be able to accommodate execution environments of various granularities (from grid computing, to Internet-based applications, to mobile applications, to embedded systems) and incorporate on-demand different technical services. This challenge will be conducted by designing a micro-kernel for software components. This micro-kernel will contain a well-defined set of core concepts, which are at the root of all component models. Several concrete software component models will then be derived from this micro-kernel.

3.1.3. Context-Aware Computing (CAC)

In adaptive systems, the notion of "*context*" becomes increasingly important. For example, mobile devices sense the environment they are in and react accordingly. This is usually enabled by a set of rules that infer how to react given a certain situation. In the Ambient/Ubiquitous/Pervasive domain [1], CAC is commonly referred to as the new paradigm that employs this idea of context in order to enmesh computing in our daily lives [72]. Many efforts that exist today focus on human-computer interaction based on context. On the one hand, computational models, middleware, and programming languages are being developed to take

[1] These terms are more or less equivalent.

the inherent characteristics of multi-scale environments into account, such as connection volatility, ambient resources, etc. An important challenge is to bridge the gap between the domain level and the computational level. The former is concerned with the expected behavior of the system from a user's viewpoint, such as how and when a system responds to changes in the context, when information can be made public, etc. On the other hand, the computational level deals with the inherent and very stringent hardware phenomena of multi-scale environments. Nevertheless, both levels have to coexist: the computational level needs to be steered by the concepts, behavior and rules which exist at the domain level, whereas the domain needs to adapt to the specificities of the ever changing environment that is monitored and managed by the computational level. In order to address this challenge, we first intend to investigate representations at the domain level of concepts such as user profile, local positioning information and execution context [83]. Furthermore, a mapping has to be devised between these concepts and generic concepts at the computational level, the latter being as independent as possible from concrete platforms or languages. This mapping has to be bidirectional: the computational level needs to be steered by the concepts, behavior and rules that exist at the domain level, whereas the domain needs to adapt to the particulars of the ever-changing environment that is monitored and managed at the computational level. Furthermore, the mapping has to be dynamic since the changes have to be propagated between the levels at run time. An explicit domain level is not only useful for bridging the aforementioned gap, but also for designing and developing open task-specific languages at the domain level, which allow users to dynamically adapt the behavior of the applications in multi-scale environments in well-defined ways.

We will base the design approach of the future implementation prototype on Model Driven Engineering (MDE). The goal of MDE [80] consists of developing, maintaining and evolving complex software systems by raising the level of abstraction from source code to models. The latter is in our case the domain level, which will be connected to the computational level by means of MDE techniques. One added benefit of MDE is that it provides means for managing model inconsistencies.

3.2. Two Research Directions

We propose to follow two research directions to foster software reuse and adaptation. The first direction, that could be coined as the spatial dimension of adaptation, will provide middleware platforms to let applications be adapted to changing execution contexts. The second direction, the so-called temporal dimension of adaptation, will provide concepts and artifacts to let designers specify evolvable applications.

3.2.1. Adaptable Component Frameworks for Middleware

As a cornerstone of next generation software, adaptation is a property which must be present throughout the entire life cycle, from design to execution. We develop then a vision where adaptation is not only a property that is desirable for end-user applications, but also for the middleware platform that executes these applications. Until now, middleware is a rather specialized activity where each new environment forces the development of a corresponding platform, which is specific to the given environment. This has led to a large number of platforms (from Web Services, to EJB, to CORBA, to ad hoc middleware for embedded systems). Although at a high level, solutions for communication interoperability often exist between these platforms, they stay loosely coupled and separated. Furthermore, the concepts which are at the core of these platforms and their architectures are too different to allow, for example, sharing technical services.

The research challenge that we propose here is to define and develop middleware and associated services which could be adapted to a broad range of environments from grid computing, to Internet-based applications, to local networks, to mobile applications on PDA's and smart phones, to embedded systems. The benefits of that are twofold. First, it enables the easier deployment of mobile applications in different environments by taking advantage of the common ground provided by adaptable middleware. Second, middleware is a rapidly changing domain where new technologies appear frequently. Yet, up to now, each new technological shift has imposed a complete re-development of the middleware. Having a common ground on which middleware is built would help in such transitions by fostering reuse. In terms of industrial output, the impact of these results will also be helpful for software editors and companies to adapt their products more rapidly to new and emerging middleware technologies.

This research challenge has close links with MDE and product line families. We believe that the added value of our proposal is to cover a more integrated solution: we are not only interested in middleware design with MDE technologies, but we also wish to integrate them with software component technologies and advanced programming techniques, such as AOP. We will then cover a broad spectrum of middleware construction, from design (MDE) to implementation (CBSE) to application development (AOP).

3.2.2. Distributed Application Design for Adaptive Platforms

Considering adaptation in the first design steps of an application allows for its preparation and follow-up during the entire life-cycle. As mentioned previously, some software paradigms help already in the design and the development of adaptable applications. AOSD proposes separation of concerns and weaving of models in order to increase the mastering and the evolution of software. MDE consists of evolving complex software systems by raising the level of abstraction from source code to models. Several programming approaches, such as AOP or reflective approaches, have gained in popularity to implement flexibility. Other approaches, such as CBSE, propose compositional way for reuse and compose sub-systems in the application building. Finally, context-aware programming for mobile environment proposes solutions in order to consider context evolution. Overall, the objective of these approaches is to assist the development of applications that are generic and that can be adapted with respect to the properties of the domain or the context.

The research challenge that we propose to address here is similar to static points of variation in product line families. We plan to study dynamic points of variation in order to take into account adaptation in the first design steps and to match this variation. The first research challenge is the introduction of elements in the modeling phase that allow the specification of evolution related properties. These properties must make it possible to build safe and dynamic software architectures. We wish to express and validate properties in the entire software life cycle. These properties are functional, non-functional, static, behavioral, or even qualitative properties. We also want to be able to check that all the properties are present, that the obtained behavior is the expected one, and that the quality of service is not degraded after the addition or the withdrawal of functionalities. We will base our approach on the definition of contracts expressed in various formalisms (*e.g.*, first order logic, temporal logic, state automata) and we will propose a composition of these contracts.

The second challenge will be to implement design processes that maintain coherence between the various stages of modeling in a MDE approach of the applications, as well as maintaining coherence between the phases of modeling and implementation. To do so, we will design and implement tools that will enable traceability and coherence checking between models, as well as between models and the application at execution time.

Finally, we will introduce context information in the development process. At the modeling level, we will represent concepts, behavior and rules of adaptive systems to express adaptation abstraction. These models will be dynamic and connected to implementation levels at the computational level and they will consider context knowledge. The goal is to bridge the gap between the computational level and the domain level in adaptive systems by synchronization of models and implementations, but also by representation of such common knowledge.

ARLES Project-Team

3. Research Program

3.1. Introduction

Research undertaken within the ARLES project-team aims to offer comprehensive solutions to support the development of pervasive computing systems that are dynamically composed according to networked resources in the environment. This leads the team to investigate methods and tools supporting the engineering of pervasive software systems, with a special emphasis on associated middleware solutions.

3.2. Engineering Pervasive Software Systems

Since its emergence, middleware has proved successful in assisting distributed software development, making development faster and easier, and significantly promoting software reuse while overcoming the heterogeneity of the distributed infrastructure. As a result, middleware-based software engineering is central to the principled development of pervasive computing systems. In this section, we (i) discuss challenges that middleware brings to software engineering, and (ii) outline a revolutionary approach to middleware-based software engineering aiming at the dynamic runtime synthesis of connectors, a.k.a *emergent middleware*.

3.2.1. Middleware-based Software Engineering

Middleware establishes a new software layer that homogenizes the infrastructure's diversities by means of a well-defined and structured distributed programming model, relieving software developers from low-level implementation details, by: (i) at least abstracting transport layer network programming via high-level network abstractions matching the application computational model, and (ii) possibly managing networked resources to offer quality of service guarantees and/or domain specific functionalities, through reusable middleware-level services. More specifically, middleware defines:

- A resource definition language that is used for specifying data types and interfaces of networked software resources;
- A high-level addressing scheme based on the underlying network addressing scheme for locating resources;
- Interaction paradigms and semantics for achieving coordination;
- A transport/session protocol for achieving communication; and
- A naming/discovery protocol with related registry structure and matching relation for publishing and discovering the resources available in the given network.

Attractive features of middleware have made it a powerful tool in the software system development practice. Hence, middleware is a key factor that has been and needs to be further taken into account in the Software Engineering (SE) discipline [5]. The advent of middleware standards have further contributed to the systematic adoption of this paradigm for distributed software development.

[5] W. Emmerich. Software Engineering and Middleware: a roadmap. In Proceedings of the Conference on the Future of Software Engineering, Limerick, Ireland, Jun. 2000.

In spite of the above, mature engineering methodologies to comprehensively assist the development of middleware-based software systems, from requirements analysis to deployment and maintenance, are lagging behind. Indeed, systematic software development accounting for middleware support is rather the exception than the norm, and methods and related tools are dearly required for middleware-based software engineering. This need becomes even more demanding if we consider the diversity and scale of today's networking environments and application domains, which makes middleware and its association with applications highly complex [5], raising new, challenging requirements for middleware. Among those, access to computational resources should be open across network boundaries and dynamic due to the potential mobility of host- and user-nodes. This urges middleware to support methods and mechanisms for description, dynamic discovery and association, late binding, and loose coordination of resources. In such variable and unpredictable environments, operating not only according to explicit system inputs but also according to the context of system operation becomes of major importance, which should be enabled by the middleware. Additionally, the networking infrastructure is continuing to evolve at a fast pace, and suggesting new development paradigms for distributed systems, calling for next-generation middleware platforms and novel software engineering processes integrating middleware features in all phases of the software development.

3.2.2. Beyond Middleware-based Architectures for Interoperability

As discussed above, middleware stands as the conceptual paradigm to effectively network together heterogeneous systems, specifically providing upper layer interoperability. That said, middleware is yet another technological block, which creates islands of networked systems.

Interoperable middleware has been introduced to overcome middleware heterogeneity. However, solutions remain rather static, requiring either use of a proprietary interface or a priori implementation of protocol translators. In general, interoperability solutions solve protocol mismatch among middleware at syntactic level, which is too restrictive. This is even truer when one considers the many dimensions of heterogeneity, including software, hardware and networks, which are currently present in ubiquitous networking environments, and that require fine tuning of the middleware according to the specific capacities embedded within the interacting parties. Thus, interoperable middleware can at best solve protocol mismatches arising among middleware aimed at a specific domain. Indeed, it is not possible to a priori design a universal middleware solution that will enable effective networking of digital systems, while spanning the many dimensions of heterogeneity currently present in networked environments and further expected to increase dramatically in the future.

A revolutionary approach to the seamless networking of digital systems is to synthesize connectors on the fly, via which networked systems communicate. The resulting emergent connectors then compose and further adapt the interaction protocols run by the connected systems, from the application layer down to the middleware layer. Hence, thanks to results in this new area, networked digital systems will survive the obsolescence of interaction protocols and further emergence of new ones.

We have specifically undertaken cooperative research on the dynamic synthesis of emergent connectors which shall rely on a formal foundation for connectors that allows learning, reasoning about, and adapting the interaction behavior of networked systems [6]. Further, compared to the state of the art foundations for connectors, it should operate a drastic shift by learning, reasoning about, and synthesizing connector behavior at run-time. Indeed, the use of connector specifications pioneered by the software architecture research field has mainly been considered as a design-time concern, for which automated reasoning is now getting practical even if limitations remain. On the other hand, recent effort in the semantic Web domain brings ontology-based semantic knowledge and reasoning at run-time; however, networked system solutions based thereupon are currently mainly focused on the functional behavior of networked systems, with few attempts to capture their interaction behavior as well as non-functional properties. In this new approach, the interaction protocols (both application- and middleware-layer) behavior will be learnt by observing the interactions of the networked systems, where ontology-based specification and other semantic knowledge will be exploited for generating

[6] Valérie Issarny, Bernhard Steffen, Bengt Jonsson, Gordon S. Blair, Paul Grace, Marta Z. Kwiatkowska, Radu Calinescu, Paola Inverardi, Massimo Tivoli, Antonia Bertolino, Antonino Sabetta: CONNECT Challenges: Towards Emergent Connectors for Eternal Networked Systems. In Proceedings of ICECCS 2009.

connectors on the fly. The approach specifically introduces the *emergent middleware* paradigm, from formal foundations to enabling software tools [2].

3.3. Middleware Architectures for Pervasive Computing

Today's wireless networks enable dynamically setting up temporary networks among mobile nodes for the realization of some distributed function. However, this requires adequate development support and, in particular, supporting middleware platforms for alleviating the complexity associated with the management of dynamic networks composed of highly heterogeneous nodes. In this section, we present an overview of the middleware paradigms that we leverage in our work: (i) service oriented middleware, a prominent paradigm in large distributed systems today, and (ii) middleware for wireless sensor networks, which have recently emerged as a promising platform.

3.3.1. Service Oriented Middleware

The *Service Oriented Computing*(SOC) paradigm advocates that networked resources should be abstracted as services, thus allowing their open and dynamic discovery, access and composition, and hence reuse. Due to this flexibility, SOC has proven to be a key enabler for pervasive computing [7]. Moreover, SOC enables integrating pervasive environments into broader service oriented settings: the current and especially the *Future Internet* is the ultimate case of such integration. We, more particularly, envision the Future Internet as a ubiquitous setting where services representing resources, people and things can be freely and dynamically composed in a decentralized fashion, which is designated by the notion of service choreography in the SOC. In the following, we discuss the role that *service oriented middleware* is aimed to have within our above sketched vision of the Future Internet idiom [6], of which pervasive computing forms an integral part.

From service oriented computing to service oriented middleware: In the last few years, there is a growing interest in choreography as a key concept in forming complex service-oriented systems. Choreography is put forward as a generic abstraction of any possible collaboration among multiple services, and integrates previously established views on service composition, among which service orchestration. Several different approaches to choreography modeling can be found in the literature: *Interaction-oriented* models describe choreography as a set of interactions between participants; while *process-oriented* models describe choreography as a parallel composition of the participants' business processes. *Activity-based* models focus on the interactions between the parties and their ordering, whereas the state of the interaction is not explicitly modeled or only partly modeled using variables; while *state-based* models model the states of the choreography as first-class entities, and the interactions as transitions between states.

The above modeling categorizations are applied in the ways in which: service choreographies are specified (e.g., by employing languages such as BPMN, WS-CDL, BPEL); services are discovered, selected and composed into choreographies (e.g., based on their features concerning interfaces, behavior, and non-functional properties such as QoS and context); heterogeneity between choreographed services is resolved via adaptation (e.g., in terms of service features and also underlying communication protocols); choreographies are deployed and enacted (e.g., in terms of deployment styles and execution engines); and choreographies are maintained/adapted given the independent evolution of choreographed services (e.g., in terms of availability and QoS). These are demanding functionalities that service oriented middleware should provide for supporting service choreographies. In providing these functionalities in the context of the Future Internet, service oriented middleware is further challenged by two key Future Internet properties: its *ultra large scale* as in number of users and services, and the *high degree of heterogeneity* of services, whose hosting platforms may range from that of resource-rich, fixed hosts to wireless, resource-constrained devices. These two properties call for considerable advances to the state of the art of the SOC paradigm.

[7] Valérie Issarny, Daniele Sacchetti, Ferda Tartanoglu, Françoise Sailhan, Rafik Chibout, Nicole Lévy, Angel Talamona: Developing Ambient Intelligence Systems: A Solution based on Web Services. Autom. Softw. Eng. 12(1): 101-137 (2005)

Our work in the last years has focused on providing solutions to the above identified challenges, more particularly in the domain of pervasive computing. Given the prevalence of mobile networking environments and powerful hand-held consumer devices, we consider resource constrained devices (and things, although we focus on smart, i.e., computation-enabled, things) as first-class entities of the Future Internet. Concerning middleware that enables networking mobile and/or resource constrained devices in pervasive computing environments, several promising solutions have been proposed, such as mobile Gaia, TOTA, AlfredO, or work at UCL, Carnegie Mellon University, and the University of Texas at Arlington. They address issues such as resource discovery, resource access, adaptation, context awareness as in location sensitivity, and pro-activeness in a seamless manner. Other solutions specialize in sensor networks; we, more specifically, discuss middleware for wireless sensor networks in the next section. In this very active domain of service-oriented middleware for pervasive computing environments, we have extensive expertise that ranges from lower-level cross-layer networking to higher-level semantics of services, as well as transversal concerns such as context and privacy. We have in particular worked on aspects including semantic discovery and composition of services based on their functional properties [1], heterogeneity of service discovery protocols, and heterogeneity of network interfaces [3]. Based on our accumulated experience, we are currently focusing on some of the still unsolved challenges identified above.

QoS-aware service composition: With regard to service composition in pervasive environments, taking into account QoS besides functional properties ensures a satisfactory experience to the end user. We focus here on the orchestration-driven case, where service composition is performed to fulfill a task requested by the user along with certain QoS constraints. Assuming the availability of multiple resources in service environments, a large number of services can be found for realizing every sub-task part of a complex task. A specific issue emerges in this regard, which is about selecting the best set of services (i.e., in terms of QoS) to participate in the composition, meeting user's global QoS requirements. QoS-aware composition becomes even more challenging when it is considered in the context of dynamic service environments characterized by changing conditions. As dynamic environments call for fulfilling user requests on the fly (i.e., at run-time) and as services' availability cannot be known a priori, service selection and composition must be performed at runtime. Hence, the execution time of service selection algorithms is heavily constrained, whereas the computational complexity of this problem is NP-hard.

Coordination of heterogeneous distributed systems: Another aspect that we consider important in service composition is enabling integration of services that employ different interaction paradigms. Diversity and ultra large scale of the Future Internet have a direct impact on coordination among interacting entities. Our choice of choreography as global coordination style among services should further be underpinned by support for and interoperability between heterogeneous interaction paradigms, such as message-driven, event-driven and data-driven ones. Different interaction paradigms apply to different needs: for instance, asynchronous, event-based publish/subscribe is more appropriate for highly dynamic environments with frequent disconnections of involved entities. Enabling interoperability between such paradigms is imperative in the extremely heterogeneous Future Internet integrating services, people and things. Interoperability efforts are traditionally based on, e.g., bridging communication protocols, where the dominant position is held by ESBs, wrapping systems behind standard technology interfaces, and/or providing common API abstractions. However, such efforts mostly concern a single interaction paradigm and thus do not or only poorly address cross-paradigm interoperability. Efforts combining diverse interaction paradigms include: implementing the LIME tuple space middleware on top of a publish/subscribe substrate; enabling Web services/SOAP-based interactions over a tuple space binding; and providing ESB implementations based on the tuple space paradigm.

Evolution of service oriented applications: A third issue we are interested in concerns the maintenance of service-oriented applications despite the evolution of employed services. Services are autonomous systems that have been developed independently from each other. Moreover, dynamics of pervasive environments and the Future Internet result in services evolving independently; a service may be deployed, or un-deployed at anytime; its implementation, along with its interface may change without prior notification. In addition, there are many evolving services that offer the same functionality via different interfaces and with varying quality characteristics (e.g., performance, availability, reliability). The overall maintenance process amounts to replacing a service that no longer satisfies the requirements of the employing application with a substitute service that offers the same or a similar functionality. The goal of seamless service substitution is to relate the substitute service with the original service via concrete mappings between their operations, their inputs and outputs. Based on such mappings, it is possible to develop/generate an adapter that allows the employing application to access the substitute service without any modification in its implementation. The service substitution should be dynamic and efficient, supported by a high level of automation. The state of the art in service substitution comprises various approaches. There exist efforts, which assume that the mappings between the original and the substitute service are given, specified by the application or the service providers. The human effort required makes these approaches impractical, especially in the case of pervasive environments. On the other hand, there exist automated solutions, proposing mechanisms for the derivation of mappings. The complexity of these approaches scales up with the cardinality of available services and therefore efficiency is compromised. Again, this is an important disadvantage, especially considering the case of pervasive environments.

3.3.2. Middleware for Wireless Sensor Networks

Wireless sensor networks (WSNs) enable low cost, dense monitoring of the physical environment through collaborative computation and communication in a network of autonomous sensor nodes, and are an area of active research. Owing to the work done on system-level functionalities such as energy-efficient medium access and data-propagation techniques, sensor networks are being deployed in the real world, with an accompanied increase in network sizes, amount of data handled, and the variety of applications. The early networked sensor systems were programmed by the scientists who designed their hardware, much like the early computers. However, the intended developer of sensor network applications is not the computer scientist, but the designer of the system *using* the sensor networks, which might be deployed in a building or a highway. We use the term *domain expert* to mean the class of individuals most likely to use WSNs – people who may have basic programming skills but lack the training required to program distributed systems. Examples of domain experts include architects, civil and environmental engineers, traffic system engineers, medical system designers etc. We believe that the wide acceptance of networked sensing is dependent on the ease-of-use experienced by the domain expert in developing applications on such systems.

The obvious solution to enable this ease-of-use in application development is sensor network middleware, along with related programming abstractions [8]. Recent efforts in standardizing network-layer protocols for embedded devices provide a sound foundation for research and development of middleware that assist the sensor network developers in various aspects that are of interest to us, including the following.

Data-oriented operations: A large number of WSN applications are concerned with sampling and collection of data, and this has led to a large body of work to provide middleware support to the programmer of WSNs for easy access to the data generated and needed by the constituent nodes. Initial work included Hood, and TeenyLIME, which allowed data-sharing over a limited spatial range. Further work proposed the use of the DART runtime environment, which exposes the sensor network as a distributed data-store, addressable by using logical addresses such as “all nodes with temperature sensors in Room 503”, or “all fire sprinklers in the fifth and sixth floors”, which are more intuitive than, say, IP addresses. Taking a different approach toward handling the data in the sensor network, some middleware solutions propose to manipulate them using semantic techniques, such as in the Triple Space Computing approach, which models the data shared by the nodes in the system as RDF triples (subject-predicate-object groups), a standard method for semantic data representation. They propose to make these triples available to the participating nodes using a tuple space, thus giving it the “triple space” moniker. S-APL or Semantic-Agent Programming Language uses semantic technologies to integrate the semantic descriptions of the domain resources with the semantic prescription of agent behavior.

[8] L. Mottola and G. P. Picco. Programming Wireless Sensor Networks: Fundamental Concepts and State of the Art. In ACM Computing Surveys. Volume 43, Issue 3. April 2011.

Integration with non-WSN nodes: Most of the work above focuses on designing applications that exhibit only intra-network interactions, where the interaction with the outside world is only in the form of sensing it, or controlling it by actuation. The act of connecting this data to other systems outside the sensor network is mostly done using an external gateway. This is then supported by middlewares that expose the sensor network as a database (e.g., TinyDB and Cougar), allowing the operator to access the data using a SQL-like syntax, augmented with keywords that can be used to specify the rate of sampling, for example. Another direction of integrating WSNs in general with larger systems such as Web servers has been toward using REST (REpresentational State Transfer) technologies, which are already used for accessing services on the Web as a lightweight alternative to SOAP. There has also been work proposing a system that will enable heterogeneous sensors and actuators to expose their sensing and actuation capabilities in a plug and play fashion. It proposes a middleware that defines a set of constraints, support services and interaction patterns that follow the REST architectural style principles, using the ATOM Web publishing protocol for service description, and a two-step discovery process. Additionally, there has been work in implementation of a REST-oriented middleware that runs on embedded devices such as Sun SPOT nodes, and the Plogg wireless energy monitors. This involves a two-fold approach — embedding tiny Web servers in devices that can host them, and employing a proxy server in situations where that is not the case. However, it has been noticed that the abstractions provided by REST might be too simplistic to compose complex applications over the services provided by WSN nodes. Some of the most recent work in this area also proposes to convert existing (network-layer) gateways into smart gateways, by running application code on them.

In addition to supporting the above interactions, sensor network middleware has also been proposed to address the challenges arising from the fact that a particular sensor or actuator may not be always available. This leads to the need for transparent reconfiguration, where the application developer should not have to care about reliability issues. The PIRATES event-based middleware for resource-rich nodes (hosting sensors/actuators, or just processing data) includes a third-party-remapping facility that can be used to remap a component's endpoints without affecting the business logic. In that sense, it is similar to the RUNES middleware targeted at embedded systems.

Finally, we also note the recent initial WSN middleware research focused on the new nascent classes of systems. Most recently, the field of *participatory sensing*[9] has emerged, where the role of sensing is increasingly being performed by the mobile phones carried by the users of the system, providing data captured using the sound, GPS, accelerometer and other sensors attached to them. This has led to the emergence of middleware such as JigSaw. The core additional challenges in this domain come from the inherent mobility of the nodes, as well as their extremely large scale [4].

[9] Lane, N.D.; Miluzzo, E.; Hong Lu; Peebles, D.; Choudhury, T.; Campbell, A.T.; , "A survey of mobile phone sensing," Communications Magazine, IEEE , vol.48, no.9, pp.140-150, Sept. 2010

LOGNET Team

3. Research Program

3.1. Introduction

We study overlay networks and peer-to-peer systems. Our skills are applied to studying protocols to interconnect heterogeneous networks, while guaranteeing backward compatibility. We experiment with those networks and systems in various fields, such as social networks and video streaming.

We design and implement a generic social platform, which is able to “program” and “run” (in a cloud based platform hosting a NoSQL data base) generic social networks. This is the first step towards a full decentralized P2P-based social network platform.

We also study Trust and Reputation Systems for P2P networks, and for Network Web Economy.

The final objective of those research veins is to move the computer and the computability at the edge of the network.

As another topic, we also study logics and type theory for improving proof assistants based on the Curry-Howard Isomorphism.

ASAP Project-Team

3. Research Program

3.1. Distributed computing

Distributed computing [1] was born in the late seventies when people started taking into account the intrinsic characteristics of physically distributed systems. The field then emerged as a specialized research area distinct from networks, operating systems and parallelism. Its birth certificate is usually considered as the publication in 1978 of Lamport's most celebrated paper "*Time, clocks and the ordering of events in a distributed system*" [60] (that paper was awarded the Dijkstra Prize in 2000). Since then, several high-level journals and (mainly ACM and IEEE) conferences have been devoted to distributed computing. The distributed systems area has continuously been evolving, following the progresses of all the above-mentioned areas such as networks, computing architecture, operating systems.

The last decade has witnessed significant changes in the area of distributed computing. This has been acknowledged by the creation of several conferences such as NSDI and IEEE P2P. The NSDI conference is an attempt to reassemble the networking and system communities while the IEEE P2P conference was created to be a forum specialized in peer-to-peer systems. At the same time, the EuroSys conference originated as an initiative of the European Chapter of the ACM SIGOPS to gather the system community in Europe.

3.2. Theory of distributed systems

Finding models for distributed computations prone to asynchrony and failures has received a lot of attention. A lot of research in this domain focuses on what can be computed in such models, and, when a problem can be solved, what are its best solutions in terms of relevant cost criteria. An important part of that research is focused on distributed computability: what can be computed when failure detectors are combined with conditions on process input values for example. Another part is devoted to model equivalence. What can be computed with a given class of failure detectors? Which synchronization primitives is a given failure class equivalent to? These are among the main topics addressed in the leading distributed computing community. A second fundamental issue related to distributed models, is the definition of appropriate models suited to dynamic systems. Up to now, the researchers in that area consider that nodes can enter and leave the system, but do not provide a simple characterization, based on properties of computation instead of description of possible behaviors [61], [55], [56]. This shows that finding dynamic distributed computing models is today a "Holy Grail", whose discovery would allow a better understanding of the essential nature of dynamic systems.

3.3. Peer-to-peer overlay networks

A standard distributed system today is related to thousands or even millions of computing entities scattered all over the world and dealing with a huge amount of data. This major shift in scalability requirements has lead to the emergence of novel computing paradigms. In particular, the peer-to-peer communication paradigm imposed itself as the prevalent model to cope with the requirements of large scale distributed systems. Peer-to-peer systems rely on a symmetric communication model where peers are potentially both clients and servers. They are fully decentralized, thus avoiding the bottleneck imposed by the presence of servers in traditional systems. They are highly resilient to peers arrivals and departures. Finally, individual peer behavior is based on a local knowledge of the system and yet the system converges toward global properties.

[1] This is an extract from Michel Raynal's new book [42].

A peer-to-peer overlay network logically connects peers on top of IP. Two main classes of such overlays dominate, structured and unstructured. The differences relate to the choice of the neighbors in the overlay, and the presence of an underlying naming structure. Overlay networks represent the main approach to build large-scale distributed systems that we retained. An overlay network forms a logical structure connecting participating entities on top of the physical network, be it IP or a wireless network. Such an overlay might form a structured overlay network [62], [63], [64] following a specific topology or an unstructured network [59], [65] where participating entities are connected in a random or pseudo-random fashion. In between, lie weakly structured peer-to-peer overlays where nodes are linked depending on a proximity measure providing more flexibility than structured overlays and better performance than fully unstructured ones. Proximity-aware overlays connect participating entities so that they are connected to close neighbors according to a given proximity metric reflecting some degree of affinity (computation, interest, etc.) between peers. We extensively use this approach to provide algorithmic foundations of large-scale dynamic systems.

3.4. Epidemic protocols

Epidemic algorithms, also called gossip-based algorithms [58], [57], constitute a fundamental topic in our research. In the context of distributed systems, epidemic protocols are mainly used to create overlay networks and to ensure a reliable information dissemination in a large-scale distributed system. The principle underlying technique, in analogy with the spread of a rumor among humans via gossiping, is that participating entities continuously exchange information about the system in order to spread it gradually and reliably. Epidemic algorithms have proved efficient to build and maintain large-scale distributed systems in the context of many applications such as broadcasting [57], monitoring, resource management, search, and more generally in building unstructured peer-to-peer networks.

3.5. Malicious process behaviors

When assuming that processes fail by simply crashing, bounds on resiliency (maximum number of processes that may crash), number of exchanged messages, number of communication steps, etc. either in synchronous and augmented asynchronous systems (recall that in purely asynchronous systems some problems are impossible to solve) are known. If processes can exhibit malicious behaviors, these bounds are seldom the same. Sometimes, it is even necessary to change the specification of the problem. For example, the consensus problem for correct processes does not make sense if some processes can exhibit a Byzantine behavior and thus propose an arbitrary value. In this case, the validity property of consensus, which is normally "a decided value is a proposed value", must be changed to "if all correct processes propose the same value then only this value can be decided." Moreover, the resilience bound of less than half of faulty processes is at least lowered to "less than a third of Byzantine processes." These are some of the aspects that underlie our studies in the context of the classical model of distributed systems, in peer-to-peer systems and in sensor networks.

3.6. Online social networks

Social Networks have rapidly become a fundamental component of today's distributed applications. Web 2.0 applications have dramatically changed the way users interact with the Internet and with each other. The number of users of websites like Flickr, Delicious, Facebook, or MySpace is constantly growing, leading to significant technical challenges. On the one hand, these websites are called to handle enormous amounts of data. On the other hand, news continue to report the emergence of privacy threats to the personal data of social-network users. Our research aims to exploit our expertise in distributed systems to lead to a new generation of scalable, privacy-preserving, social applications.

ATLANMOD Project-Team

3. Research Program

3.1. MDE Foundations

Traditionally, models were often used as initial design sketches mainly aimed for communicating ideas among developers. On the contrary, MDE promotes models as the primary artifacts that drive all software engineering activities (i.e. not only software development but also evolution, reverse engineering, interoperability and so on) and are considered as the unifying concept [43]. Therefore, rigorous techniques for model definition and manipulation are the basis of any MDE framework.

The MDE community distinguishes three levels of models: (terminal) model, metamodel, and metametamodel. A terminal model is a (partial) representation of a system/domain that captures some of its characteristics (different models can provide different knowledge views on the domain and be combined later on to provide a global view). In MDE we are interested in terminal models expressed in precise modeling languages. The abstract syntax of a language, when expressed itself as a model, is called a metamodel. A complete language definition is given by an abstract syntax (a metamodel), one or more concrete syntaxes (the graphical or textual syntaxes that designers use to express models in that language) plus one or more definition of its semantics. The relation between a model expressed in a language and the metamodel of that language is called *conformsTo*. Metamodels are in turn expressed in a modeling language called metamodeling language. Similar to the model/metamodel relationship, the abstract syntax of a metamodeling language is called a metametamodel and metamodels defined using a given metamodeling language must conform to its metametamodel. Terminal models, metamodels, and metametamodel form a three-level architecture with levels respectively named M1, M2, and M3. A formal definition of these concepts is provided in [50] and [44]. MDE promotes *unification by models*, like object technology proposed in the eighties *unification by objects* [42]. These MDE principles may be implemented in several standards. For example, OMG proposes a standard metametamodel called Meta Object Facility (MOF) while the most popular example of metamodel in the context of OMG standards is the UML metamodel.

In our view the main way to automate MDE is by providing model manipulation facilities in the form of model transformation operations that taking one or more models as input generate one or more models as output (where input and output models are not necessarily conforming to the same metamodel). More specifically, a model transformation Mt defines the production of a model Mb from a model Ma. When the source and target metamodels (MMs) are identical ($MMa = MMb$), we say that the transformation is endogenous. When this is not the case ($MMa \neq MMb$) we say the transformation is exogenous. An example of an endogenous transformation is a UML refactoring that transforms public class attributes into private attributes while adding accessor methods for each transformed attribute. Many other operations may be considered as transformations as well. For example verifications or measurements on a model can be expressed as transformations [46]. One can see then why large libraries of reusable modeling artifacts (mainly metamodels and transformations) will be needed.

Another important idea is the fact that a model transformation is itself a model [4]. This means that the transformation program Mt can be expressed as a model and as such conforms to a metamodel MMt. This allows an homogeneous treatment of all kinds of terminal models, including transformations. Mt can be manipulated using the same existing MDE techniques already developed for other kinds of models. For instance, it is possible to apply a model transformation Mt' to manipulate Mt models. In that case, we say that Mt' is a higher order transformation (HOT), i.e. a transformation taking other transformations (expressed as transformation models) as input or/and producing other transformations as output.

As MDE developed, it became apparent that this was a branch of language engineering [45]. In particular, MDE offers an improved way to develop DSLs (Domain-Specific Languages). DSLs are programming or modeling languages that are tailored to solve specific kinds of problems in contrast with General Purpose Languages (GPLs) that aim to handle any kind of problem. Java is an example of a programming GPL and UML an example of a modeling GPL. DSLs are already widely used for certain kinds of programming; probably the best-known example is SQL, a language specifically designed for the manipulation of relational data in databases. The main benefit of DSLs is that they allow everybody to write programs/models using the concepts that actually make sense to their domain or to the problem they are trying to solve (for instance Matlab has matrices and lets the user express operations on them, Excel has cells, relations between cells, and formulas and allows the expression of simple computations in a visual declarative style, etc.). As well as making domain code programmers more productive, DSLs also tend to offer greater optimization opportunities. Programs written with these DSLs may be independent of the specific hardware they will eventually run on. Similar benefits are obtained when using modeling DSLs. In MDE, new DSLs can be easily specified by using the metamodel concept to define their abstract syntax. Models specified with those DSLs can then be manipulated by means of model transformations (with ATL for example [8]).

When following the previously described principles, one may take advantage of the uniformity of the MDE organization. As an example, considering similarly models of the static architecture and models of the dynamic behavior of a system allows at the same time economy of concepts and economy of implementation.

The following sections describe the main MDE research challenges the team is addressing. They go beyond the development of core MDE techniques (topic on which the team, as mentioned above, has largely contributed in the past, and that we believe is quite well-covered already) and focus on new aspects that are critical for the successful application of MDE in industrial contexts.

3.2. Reverse Engineering

One important domain that is being investigated by the AtlanMod team is the reverse engineering of existing IT systems. We do believe that efficiently dealing with such legacy systems is one of the main challenges in Software Engineering and related industry today. Having a better understanding of these systems in order to document, maintain, improve or migrate them is thus a key requirement for both academic and industrial actors in this area. However, it is not an easy task and it still raises interesting challenging issues to be explored [48].

We have shown how reverse engineering practices may be advantageously revisited with the help of the MDE approach and techniques, applying (as base principle) the systematic representation as models of the required information discovered from the legacy software artifacts (e.g. source code, configuration files, documentation, metadata, etc). The rise in abstraction allowed by MDE can bring new hopes that reverse engineering is now able to move beyond more traditional ad-hoc practices. For instance, a industrial PhD in partnership with IBM France aims to investigate the possibilities of conceptualizing a generic framework enabling the extraction of business rules from a legacy application, as much as possible, independently of the language used to code it. Moreover, different pragmatic solutions for improving the overall scalability when dealing with large-scale legacy systems (handling huge data volumes) are intensively studied by the team.

In this context, AtlandMod has set up within the past years and is still developing the open source Eclipse MoDisco project (see 5.2). MoDisco is notably being referenced by the OMG ADM (Architecture Driven Modernization) normalization task force as the reference implementation for several of its standard metamodels. It is also used practically and improved in various collaborative projects the team is currently involved in (e.g. FP7 ARTIST).

We have also opened a novel research line focused on integration of APIs into MDE. In the application of reverse engineering processes while modernizing software system it is very common to face the need of integrating Application Programming Intefaces (APIs). Indeed, building any application usually involves managing a plethora of APIs to access different software assets such as: basic infrastructures (e.g. operating system, databases, or middleware), general-purpose or domain specific libraries, frameworks, software components, web services, and even other applications. Thus, to promote the interoperability between the API and model technical spaces, we have developed API2MoL, which is an approach aimed at automating the implementation of API-MDE bridges. This new language allows defining mappings between the artefacts of a given API (e.g. API classes in object-oriented APIs) and the elements of a metamodel that represents this API in the MDE technical space. A mapping definition provides the information which is necessary to build a bridge for a concrete API specification and metamodel. Thanks to the API-MDE bridges automatically created, developers are liberated from having to manually implement the tasks of obtaining models from API objects and generating such objects from models. Therefore, API2MoL may improve the productivity and quality of the part of the MDE application that deals with the APIs.

Reverse engineering techniques have also been used in the context of the Web. In the last years the development of Web APIs has become a discipline that companies have to master to succeed in the Web. The so-called API economy requires, on the one hand, companies to provide access to their data by means of Web APIs and, on the other hand, web developers to study and integrate such APIs into their applications. The exchange of data with these APIs is usually performed by using JSON, a schemaless data format easy for computers to parse and use. While JSON data is easy to read, its structure is implicit, thus entailing serious problems when integrating APIs coming from different vendors. Web developers have therefore to understand the domain behind each API and study how they can be composed. We tackle this problem by developing a MDE-based process able to reverse engineer the domain of Web APIs and to identify composition links among them. The approach therefore allows developers to easily visualize what is behind the API and the connections points that may be used in their applications.

3.3. Security Engineering

Several components are required to build up a system security architecture, such as firewalls, database user access control, intrusion detection systems, and VPN (Virtual Private Network) routers. These components must be properly configured to provide an appropriate degree of security to the system. The configuration process is highly complex and error-prone. In most organizations, security components are either manually configured based on security administrators expertise and flair; or simply recycled from existing configurations already deployed in other systems (even if they may not be appropriated for the current one). These practices put at risk the security of the whole organization.

We have started a Phd thesis in this domain intended to investigate the construction of a model-driven automatic reverse engineering mechanism (implemented as an extension of the MoDisco project) capable of analyzing deployed security aspects of components (e.g. concrete firewall configurations) to derive the abstract model (e.g. network security global policy) that is actually enforced over the system. Once the model is obtained, it can be reconciled with the expected security directives, to check its compliance, can be queried to test consistency or used in a process of forward engineering to generate validated security configurations.

As a first step we intend to apply model-driven techniques for the extraction of high level model representations of security policies enforced by firewalls. Firewalls, core components in network security systems, are generally configured by using very low level vendor specific rule-based languages, difficult to understand and to maintain. As a consequence, as the configuration files grow, understanding which security policy is being actually enforced or checking if inconsistencies has been introduced becomes a very complex and time consuming task. We propose to raise the level of abstraction so that the user can deal directly with the high level policies. Once a model representation of the enforced policy is available, model-driven techniques will ease some of the tasks we need to perform, like consistency checking, validation, querying and visualization. Easy migration between different firewall vendors will be also enabled.

3.4. Software Quality

As with any type of production, an essential part of software production is determining the quality of the software. The level of quality associated to a software product is inevitably tied to properties such as how well it was developed and how useful it is to its users. AtlanMod team focus on researching techniques for the formal verification and testing of software models and model transformations.

These techniques must be applied at the model level (to evaluate the quality of specific software designs) and at the metamodel level (to evaluate the quality of modeling languages). In both cases, the Object Constraint Language (OCL) of the OMG is widely accepted as a standard textual language to complement (meta)model specifications with all those rules/constraints that cannot be easily defined using graphical modeling constructs.

Among all possible properties to verify, we take as the basic property the *satisfiability* property, from which many others may be derived (as liveliness, redundancy, subsumption,...). Satisfiability checks whether it is possible to create a valid instantiation (i.e. one that respects all modeling constraints) of a give (meta)model. Satisfiability is an undedicable problem when general OCL constraints are used as part of the model definition.

To deal with this problem, the team maintains the tool EMFtoCSP which translates the model verification challenge into the domain of constraint logic programming (CLP) for which sophisticated decision procedures exist. The tool integrates the described functionality in the Eclipse Modeling Framework (EMF) and the Eclipse Modeling Tools (MDT), making the functionality available for MDE in practice.

To complement these formal verification techniques we are also working on testing techniques, specially to optimize the testing of model transformations. White-box testing for model transformations is a technique that involves the extraction of knowledge embedded in the transformation code to generate test models. In our work, we apply static analysis techniques to model transformation specifications and represent the extracted knowledge as partial models that can drive the generation of highly effective test models (specially in terms of coverage).

3.5. Collaborative Development

Software development processes are collaborative in nature. The active participation of end-users in the early phases of the software development life-cycle is key when developing software. Among other benefits, the collaboration promotes a continual validation of the software to be build, thus guaranteeing that the final software will satisfy the users' needs. In this context, we have opened two novel research lines focused on the collaborative development *in* MDE and the collaborative development *with* MDE. The former is aimed at promoting the collaboration in the context of MDE while the latter uses MDE techniques to promote the participation in software development processes.

Collaboration is important in the context of MDE, in particular, when creating Domain-Specific Modeling Languages (DSMLs) which are (modeling) languages specifically designed to carry out the tasks of a particular domain. While end-users are actually the experts of the domain for which a DSML is developed, their participation in the DSML specification process is still rather limited nowadays (they are normally only involved in providing domain knowledge or testing the resulting language). This means that the MDE technical experts and not end-users are the ones in control of the DSML construction and evolution. This is a problem because errors in understanding the domain may hamper the development process and the quality of the resulting DSML. Thus, it would be beneficial to promote a more active participation of end-users in the DSML development process.

We have been working on the required support to make effective this participation, in particular, we have developed Collaboro, an approach which enables the involvement of the community (i.e., end-users and developers) in the DSML creation process. Collaboro allows modeling the collaborations between community members taking place during the definition of a new DSML and supports both the collaborative definition of the abstract (i.e., metamodel) and concrete (i.e., notation) syntaxes for DSMLs by providing specific constructs to enable the discussion. Thus, each community member will have the chance to request changes, propose solutions and give an opinion (and vote) about those from others. We believe this discussion will enrich the language definition significantly and ensure that the end result satisfies as much as possible the expectations of the end-users. Collaboro has also been extended to support the example-driven development of DSMLs, thus promoting the engagement of end-users in the process.

The lessons learnt from this MDE-focused collaboration research are now being applied to the more general context of software development. In particular, our interest is to study how software development processes are governed (i.e. how the collaboration among developers and user takes place). Any software development project has to cope with a huge number of tasks consisting of either implementing new issues or fixing bugs. Thus, effective and precise prioritization of these tasks is key for the success of the project. Governance rules enable the coordination of developers in order to advance the project. Despite their importance, in practice governance rules are hardly ever explicitly defined, specially in the context of Open Source Systems (OSS), where it is hard to find a explicit system-level design, a project plan, schedule or list of deliverables. To alleviate this situation, mechanisms to facilitate the communication and the assignment of work are considered crucial for the success of the development. Tracking and issue-tracking systems, mailing lists and forums are broadly used to manage the tasks to be performed. While these tools provide a convenient compartmentalization of work and effective means of communication, they fall short in providing adequate support for specifying and enforcing governance rules (e.g. supporting the voting of tasks, easy tracking of decisions made in the project, etc.).

Thus, we believe the explicit definition of governance rules along with the corresponding infrastructure to help developers follow them would have several benefits, including improvements in the transparency of the decision-making process, traceability (being able to track why a decision was made and who decided it) and the automation of the governance process (e.g. liberating developers from having to be aware and follow the rules manually, minimizing the risk of inconsistent behaviour in the evolution of the project). We resort on MDE techniques to tackle this problem and provide a DSL specially adapted to the domain of governance in software projects to let project managers easily define the governance rules of their projects.

3.6. Scalability

As MDE is increasingly applied to larger and more complex industrial applications, the current generation of modelling and model management technologies are being stressed to their limits in terms of their capacity to accommodate collaborative development, efficient management and persistence of models larger than a few hundreds of megabytes in size. Additional research and development is imperative in order to enable MDE to remain relevant with industrial practice and to continue delivering its widely recognised productivity, quality, and maintainability benefits. Achieving scalability in modelling and MDE involves being able to construct large models and domain-specific languages in a systematic manner, enabling teams of modellers to construct and refine large models in a collaborative manner, advancing the state-of-the-art in model querying and transformations tools so that they can cope with large models (of the scale of millions of model elements), and providing an infrastructure for efficient storage, indexing and retrieval of large models. AtlanMod wants to provide a solution for these aspects of scalability in MDE by extending the Eclipse modeling framework, to create an open-source solution to scalable modeling in industry.

3.7. Industrialization of open source tools

Research labs, as a source of innovation, are potential key actors of the Software Engineering market. However, an important collaborative effort with the other players in the software industry is still needed in order to actually transfer the corresponding techniques or technologies from the research lab to a company. Based on the AtlanMod concrete experience with the previously mentioned open source tools/projects, we have extracted a pragmatic approach [3] for transforming the results of scientific experimentation into practical industrial solutions.

While dealing with innovation, this approach is also innovation-driven itself, as the action is actually conducted by the research lab via a technology transfer. Three different partners are directly involved in this process, using open source as the medium for maintaining a constant interaction between all of them:

- **Use Case Provider.** Usually a company big enough to have to face real complex industrial scenarios which need to be solved (at least partially) by applying new innovative principles and techniques;
- **Research Lab.** Usually a group from a research institute (public or private) or university evaluating the scientific relevance of the problems, identifying the research challenges and prototyping possible solutions;
- **Technology Provider.** Usually a small or medium company, with a particular technical expertise on the given domain or Software Engineering field, building and delivering the industrial version of the designed solutions;

From our past and current experience, three main characteristics of this industrialization *business model* can be highlighted:

- **Win-win situation.** Each partner can actually focus on its core activity while also directly benefiting from the results obtained by the others (notably the research lab can continue to do research);
- **Application-driven context.** The end-user need is at the origin of the process, which finally makes the developed solution actually relevant;
- **Iterative process.** The fact of having three distinct partners requires different regular and consecutive exchanges between all of them.

CIDRE Project-Team

3. Research Program

3.1. Our perspective

For many aspects of our everyday life, we rely heavily on information systems, many of which are based on massively networked devices that support a population of interacting and cooperating entities. While these information systems become increasingly open and complex, accidental and intentional failures get considerably more frequent and severe.

Two research communities traditionally address the concern of accidental and intentional failures: the distributed computing community and the security community. While both these communities are interested in the construction of systems that are correct and secure, an ideological gap and a lack of communication exist between them that is often explained by the incompatibility of the assumptions each of them traditionally makes. Furthermore, in terms of objectives, the distributed computing community has favored systems availability while the security community has focused on integrity and confidentiality, and more recently on privacy.

By contrast with this traditional conception, we are convinced that by looking at information systems as a combination of possibly revisited basic protocols, each one specified by a set of properties such as synchronization and agreement, security properties should emerge. This vision is shared by others and in particular by Myers *et al.* [57], whose objectives are to explore new methods for constructing distributed systems that are trustworthy in the aggregate even when some nodes in the system have been compromised by malicious attackers.

In accordance with this vision, the first main characteristic of the CIDRE group is to gather researchers from the two aforementioned communities, in order to address intentional failures, using foundations and approaches coming from both communities.

The second main characteristic of the CIDRE group lies in the scope of the systems it considers. Indeed, we consider three complementary levels of study:

- The Node Level: The term node either refers to a device that hosts a network client or service or to the process that runs this client or service. Node security management must be the focus of a particular attention, since from the user point of view, security of his own devices is crucial. Sensitive information and services must therefore be locally protected against various forms of attacks. This protection may take a dual form, namely prevention and detection.
- The Group Level: Distributed applications often rely on the identification of sets of interacting entities. These subsets are either called groups, clusters, collections, neighborhoods, spheres, or communities according to the criteria that define the membership. Among others, the adopted criteria may reflect the fact that its members are administrated by a unique person, or that they share the same security policy. It can also be related to the localization of the physical entities, or the fact that they need to be strongly synchronized, or even that they share mutual interests. Due to the vast number of possible contexts and terminologies, we refer to a single type of set of entities, that we call set of nodes. We assume that a node can locally and independently identify a set of nodes and modify the composition of this set at any time. The node that manages one set has to know the identity of each of its members and should be able to communicate directly with them without relying on a third party. Despite these two restrictions, this definition remains general enough to include as particular cases most of the examples mentioned above. Of course, more restrictive behaviors can be specified by adding other constraints. We are convinced that security can benefit from the existence and the identification of sets of nodes of limited size as they can help in improving the efficiency of the detection and prevention mechanisms.

- The Open Network Level: In the context of large-scale distributed and dynamic systems, interaction with unknown entities becomes an unavoidable habit despite the induced risk. For instance, consider a mobile user that connects his laptop to a public Wifi access point to interact with his company. At this point, data (regardless it is valuable or not) is updated and managed through non trusted undedicated entities (i.e., communication infrastructure and nodes) that provide multiple services to multiple parties during that user connection. In the same way, the same device (e.g., laptop, PDA, USB key) is often used for both professional and private activities, each activity accessing and manipulating decisive data.

The third characteristic of the CIDRE group is to focus on three different aspects of security, namely trust, intrusion detection, and privacy as well as on the bridges that exist between these aspects. Indeed, we believe that to study new security solutions for nodes, set of nodes and open network levels, one must take into account that it is now a necessity to interact with devices whose owners are unknown. To reduce the risk to rely on dishonest entities, a trust mechanism is an essential prevention tool that aims at measuring the capacity of a remote node to provide a service compliant with its specification. Such a mechanism should allow to overcome ill-founded suspicions and to be aware of established misbehaviors. To identify such misbehaviors, intrusion detection systems are necessary. Such systems aim at detecting, by analyzing data flows, whether violations of the security policies have occurred. Finally, Privacy Protection, which is now recognized as a fundamental individual right, should be respected despite the presence of tools that continuously observe or even control users actions or behaviors.

3.2. Intrusion Detection

By exploiting vulnerabilities in operating systems, applications, or network services, an attacker can defeat the preventive security mechanisms and violate the security policy of the whole system. The goal of intrusion detection systems (IDS) is to be able to detect, by analyzing some data generated on a monitored system, violations of the security policy. From our point of view, while useful in practice, misuse detection is intrinsically limited. Indeed, it requires to update the signatures database in real-time similarly to what has to be done for antivirus tools. Given that there are thousands of machines that are every day victims of malware, such an approach may appear as insufficient especially due to the incredible expansion of malware, drastically limiting the capabilities of human intervention and response. The CIDRE group takes the alternative approach, i.e. the anomaly approach, which consists in detecting a deviation from a referenced behavior. Specifically, we propose to study two complementary methods:

- Illegal Flow Detection: This first method intends to detect information flows that violate the security policy [60], [56]. Our goal is here to detect information flows in the monitored system that are allowed by the access control mechanism, but are illegal from the security policy point of view.
- Data Corruption Detection: This second method aims at detecting intrusions that target specific applications, and make them execute illegal actions by using these applications incorrectly [54], [59]. This approach complements the previous one in the sense that the incorrect use of the application can possibly be legal from the point of view of the information flows and access control mechanisms, but is incorrect considering the security policy.

In both approaches, the access control mechanisms or the monitored applications can be either configured and executed on a single node, or distributed on a set of nodes. Thus, our approach must be studied at least at these first two levels.

To complement these two approaches, we started two years ago to study the impact that visualization could have in the context of security and particularly how it could improve intrusion detection and forensics analysis.

We finally plan to work on intrusion detection system evaluation methods. For that research, we set a priori aside no particular IDS approach or technique. Here are some concrete examples of our research goals (both short term and long term objectives) in the intrusion detection field:

- at node level, we apply the defensive programming approach (coming from the dependability field) to data corruption detection. The challenge is to determine which invariant/properties must be and can be verified either at runtime or statically. Regarding illegal flow detection, we try to extend this method to build anti-viruses by determining viruses signatures.

- at the set of nodes level, we revisit the distributed problems such as clock synchronization, logical clocks, consensus, properties detection, to extend the solutions proposed at node levels to cope with distributed flow control checking mechanisms. Regarding illegal flow detection, we study the collaboration and consistency at nodes and set of nodes levels to obtain a global intrusion detection mechanism. Regarding the data corruption detection approach, our challenge is to identify local predicates/properties/invariants so that global predicates/properties/invariants would emerge at the system level.

3.3. Privacy

In our world of ubiquitous technologies, each individual constantly leaves digital traces related to his activities and interests which can be linked to his identity. The protection of privacy is one of the greatest challenge that lies ahead and also an important condition for the development of the Information Society. Moreover, due to legality and confidentiality issues, problematics linked to privacy emerge naturally for applications working on sensitive data, such as medical records of patients or proprietary datasets of enterprises. Privacy Enhancing Technologies (PETs) are generally designed to respect both the principles of data minimization and data sovereignty. The data minimization principle states that only the information necessary to complete a particular application should be disclosed (and no more). This principle is a direct application of the legitimacy criteria defined by the European data protection directive (Article 7). This directive is currently being revised into a regulation (probably released in 2014) that is going to strengthen the privacy rights of individuals and puts forward the concept of "privacy-by-design", which integrates the privacy aspects into the conception phase of a service or product. The data sovereignty principle states that data related to an individual belong to him and that he should stay in control of how this data is used and for which purpose. This principle can be seen as an extension of many national legislations on medical data that consider that a patient record belongs to the patient, and not to the doctors that create or update it, nor to the hospital that stores it. In the CIDRE project, we investigate PETs that operate at the three different levels (node, set of nodes or open distributed system) and are generally based on a mix of different foundations such as cryptographic techniques, security policies and access control mechanisms just to name a few. Examples of domains where privacy and utility aspects collide and that will be studied within the context of CIDRE include: identity management and privacy, geo-privacy, distributed systems and privacy, privacy-preserving data mining and privacy issues in social networks. Here are some concrete examples of our research goals in the privacy field:

- at the node level, we design privacy preserving identification scheme, automated reasoning on privacy policies [58], and policy-based adaptive PETs.
- at the set of nodes level, we augment distributed algorithms (i.e., routing) with privacy properties such as anonymity, unlinkability, and unobservability.
- at the open distributed system level, we target both geo-privacy concerns (that typically occur in location-based services) and privacy issues in social networks. In the former case, we adopt a sanitization approach while in the latter one we define privacy policies at user level, and their enforcement by all the intervening actors (e.g, at the social network sites providers).

3.4. Trust Management

While the distributed computing community relies on the trustworthiness of its algorithms to ensure systems availability, the security community historically makes the hypothesis of a Trusted Computing Base (TCB) that contains the security mechanisms (such as access controls, and cryptography) that implement the security policy. Unfortunately, as information systems get increasingly complex and open, the TCB management may itself get very complex, dynamic and error-prone. From our point of view, an appealing approach is to distribute and manage the TCB on each node and to leverage the trustworthiness of the distributed algorithms in order to strengthen each node's TCB. Accordingly, the CIDRE group studies automated trust management systems at all the three identified levels:

- at the node level, such a system should allow each node to evaluate by itself the trustworthiness of its neighborhood and to self-configure the security mechanisms it implements;
- at the group level, such a system might rely on existing trust relations with other nodes of the group to enhance the significance and the reliability of the gathered information;
- at the open network level, such a system should rely on reputation mechanisms to estimate the trustworthiness of the peers the node interacts with. The system might also benefit from the information provided by a priori trusted peers that, for instance, would belong to the same group (see previous item).

For the last two items, the automated trust management system will de facto follow the distributed computing approach. As such, emphasis will be put on the trustworthiness of the designed distributed algorithms. Thus, the proposed approach will provide both the adequate security mechanisms and a trustworthy distributed way of managing them. Regarding trust management, we still have research goals that are to be tackled. We briefly list hereafter some of our short and long term objectives at node, group and open networks levels:

1. at node level, we are going to investigate how implicit trust relationships, identified and deduced by a node during its interactions with its neighborhood, could be explicitly used by the node (for instance by means of a series of rules) to locally evaluate the trustworthiness of its neighborhood. The impact of trust on the local security policy, and on its enforcement will be studied accordingly.
2. at the set of nodes level, we plan to take advantage of the pre-existing trust relationship among the set of nodes to design composition mechanisms that would guarantee that automatically configured security policies are consistent with each group member security policy.
3. at the open distributed system level, we are going to design reputation mechanisms to both defend the system against specific attacks (whitewashing, bad mouthing, ballot stuffing, isolation) by relying on the properties guaranteed at nodes and set of nodes levels, and guaranteeing persistent and safe feedback, and for specific cases in guaranteeing the right to be forgotten (i.e., the right to data erasure).

MYRIADS Project-Team

3. Research Program

3.1. Introduction

Research activity within the MYRIADS team encompasses several areas: distributed systems, middleware and programming models. We have chosen to provide a brief presentation of some of the scientific foundations associated with them: autonomic computing, future internet and SOA, distributed operating systems, and unconventional/nature-inspired programming.

3.2. Autonomic Computing

During the past years the development of raw computing power coupled with the proliferation of computer devices has grown at exponential rates. This phenomenal growth along with the advent of the Internet have led to a new age of accessibility - to other people, other applications and others systems. It is not just a matter of numbers. This boom has also led to unprecedented levels of complexity for the design and the implementation of these applications and systems, and of the way they work together. The increasing system scale is reaching a level beyond human ability to master its complexity.

This points towards an inevitable need to automate many of the functions associated with computing today. Indeed we want to interact with applications and systems intuitively, and we want to be far less involved in running them. Ideally, we would like computing systems to entirely manage themselves.

IBM [58] has named its vision for the future of computing "autonomic computing." According to IBM this new computer paradigm means the design and implementation of computer systems, software, storage and support that must exhibit the following basic fundamentals:

Flexibility. An autonomic computing system must configure and reconfigure itself under varying, even unpredictable, conditions.

Accessibility. The nature of the autonomic system is that it is always on.

Transparency. The system will perform its tasks and adapt to a user's needs without dragging the user into the intricacies of its workings.

In the Myriads team we will act to satisfy these fundamentals.

3.3. Future Internet and SOA

Traditional information systems were built by integrating applications into a communication framework, such as CORBA or with an Enterprise Application Integration system (EAI). Today, companies need to be able to reconfigure themselves; they need to be able to include other companies' business, split or externalize some of their works very quickly. In order to do this, the information systems should react and adapt very efficiently. EAIs approaches did not provide the necessary agility because they were too tightly coupled and a large part of business processes were "hard wired" into company applications.

Web services and Service Oriented Architectures (SOA) partly provide agility because in SOA business processes are completely separated from applications which can only be viewed as providing services through an interface. With SOA technologies it is easily possible to modify business processes, change, add or remove services.

However, SOA and Web services technologies are mainly market-driven and sometimes far from the state-of-the-art of distributed systems. Achieving dependability or being able to guarantee Service Level Agreement (SLA) needs much more agility of software elements. Dynamic adaptability features are necessary at many different levels (business processes, service composition, service discovery and execution) and should be coordinated. When addressing very large scale systems, autonomic behaviour of services and other parts of service oriented architectures is necessary.

SOAs will be part of the "Future Internet". The "Future Internet" will encompass traditional Web servers and browsers to support companies and people interactions (Internet of services), media interactions, search systems, etc. It will include many appliances (Internet of things). The key research domains in this area are network research, cloud computing, Internet of services and advanced software engineering.

The Myriads team will address adaptability and autonomy of SOAs in the context of Grids, Clouds and at large scale.

3.4. Distributed Operating Systems

An operating system provides abstractions such as files, processes, sockets to applications so that programmers can design their applications independently of the computer hardware. At execution time, the operating system is in charge of finding and managing the hardware resources necessary to implement these abstractions in a secure way. It also manages hardware and abstract resource sharing between different users and programs.

A distributed operating system makes a network of computer appear as a single machine. The structure of the network and the heterogeneity of the computation nodes are hidden to users. Members of the Myriads team members have a long experience in the design and implementation of distributed operating systems, for instance in Kerrighed, Vigne and XtreemOS projects.

Clouds can be defined as platforms for on-demand resource provisioning over the Internet. These platforms rely on networked computers. Three flavours of cloud platforms have emerged corresponding to different kinds of service delivery:

- IaaS (Infrastructure as a Service) refers to clouds for on-demand provisioning of elastic and customizable execution platforms (from physical to virtualized hardware).
- PaaS (Platform as a Service) refers to clouds providing an integrated environment to develop, build, deploy, host and maintain scalable and adaptable applications.
- SaaS (Software as a Service) refers to clouds providing customers access to ready-to-use applications.

The cloud computing model [48], [45] introduces new challenges in the organization of the information infrastructure: security, identity management, adaptation to the environment (costs). The organization of large organization IT infrastructures is also impacted as their internal data-centers, sometimes called private clouds, need to cooperate with resources and services provisioned from the cloud in order to cope with workload variations. The advent of cloud and green computing introduces new challenges in the domain of distributed operating systems: resources can be provisioned and released dynamically, the distribution of the computations on the resources must be reevaluated periodically in order to reduce power consumption and resource usage costs. Distributed cloud operating system must adapt to these new challenges in order to reduce cost and energy, for instance, through the redistribution of the applications and services on a smaller set of resources.

The Myriads team works on the design and implementation of system services at IaaS and PaaS levels to autonomously manage cloud and cloud federations resources and support collaboration between cloud users.

3.5. Unconventional/Nature-inspired Programming

Facing the complexity of the emerging ICT landscape in which highly heterogeneous digital services evolve and interact in numerous different ways in an autonomous fashion, there is a strong need for rethinking programming models. The question is “*what programming paradigm can efficiently and naturally express this great number of interactions arising concurrently on the platform?*”.

It has been suggested [46] that observing nature could be of great interest to tackle the problem of modeling and programming complex computing platforms, and overcome the limits of traditional programming models. Innovating unconventional programming paradigms are requested to provide a high-level view of these interactions, then allowing to clearly separate what is a matter of expression from what is a question of implementation. Towards this, nature is of high inspiration, providing examples of self-organising, fully decentralized coordination of complex and large scale systems.

As an example, chemical computing [49] has been proposed more than twenty years ago for a natural way to program parallelism. Even after significant spread of this approach, it appears today that chemical computing exposes a lot of good properties (implicit autonomy, decentralization, and parallelism) to be leveraged for programming service infrastructures.

The Myriads team will investigate nature-inspired programming such as chemical computing for autonomous service computing.

REGAL Project-Team

3. Research Program

3.1. Research rationale

As society relies more and more on computers, responsiveness, correctness and security are increasingly critical. At the same time, systems are growing larger, more parallel, and more unpredictable. Our research agenda is to design Computer Systems that remain correct and efficient despite this increased complexity and in spite of conflicting requirements. The term *"Computer Systems"* is interpreted broadly and includes systems architectures, operating systems, distributed systems, and computer networks.[1] The Regal group covers the whole spectrum, with a "bimodal" focus on distributed systems and infrastructure software. This holistic approach allows us to address related problems at different levels. It also permits us to efficiently share knowledge and expertise, and is a source of originality.

Computer Systems is a rapidly evolving domain, with strong interactions with industry. Two main evolutions in the Computer Systems area have strongly influenced our research activities:

3.1.1. Modern computer systems are increasingly parallel and distributed.

Ensuring the persistence, availability and consistency of data in a distributed setting is a major requirement: the system must remain correct despite slow networks, disconnection, crashes, failures, churn, and attacks. Ease of use, performance and efficiency are equally important for systems to be accepted. These requirements are somewhat conflicting, and there are many algorithmic and engineering trade-offs, which often depend on specific workloads or usage scenarios.

Years of research in distributed systems are now coming to fruition, and are being used by millions of users of web systems, peer-to-peer systems, gaming and social applications, or cloud computing. These new usages bring new challenges of extreme scalability and adaptation to dynamically-changing conditions, where knowledge of system state can only be partial and incomplete. The challenges of distributed computing listed above are subject to new trade-offs.

Innovative environments that motivate our research include cloud computing, geo-replication, edge clouds, peer-to-peer (P2P) systems, dynamic networks, and manycore machines. The scientific challenges are scalability, fault tolerance, security, dynamicity and the virtualization of the physical infrastructure. Algorithms designed for classical distributed systems, such as resource allocation, data storage and placement, and concurrent access to shared data, need to be revisited to work properly under the constraints of these new environments.

Regal focuses in particular on two key challenges in these areas: the adaptation of algorithms to the new dynamics of distributed systems and data management on large configurations.

3.1.2. Multicore architectures are everywhere.

The fine-grained parallelism offered by multicore architectures has the potential to open highly parallel computing to new application areas. To make this a reality, however, many issues, including issues that have previously arisen in distributed systems, need to be addressed. Challenges include obtaining a consistent view of shared resources, such as memory, and optimally distributing computations among heterogeneous architectures, such as CPUs, GPUs, and other specialized processors. As compared to distributed systems, in the case of multicore architectures, these issues arise at a more fine-grained level, leading to the need for different solutions and different cost-benefit trade-offs.

[1] As defined by the journal ACM Transactions on Computer Systems; see http://tocs.acm.org/.

Recent multicore architectures are highly diverse. Compiling and optimizing programs for such architectures can only be done for a given target. In this setting, managed runtime environments (MREs) are an elegant approach since they permit distributing a unique binary representation of an application, to which architecture-specific optimizations can be applied late on the execution machine. Finally, the concurrency provided by multicore architectures also induces new challenges for software robustness. We consider this problem in the context of systems software, using static analysis of the source code and the technology developed in the Coccinelle tool.

SCORE Team

3. Research Program

3.1. Introduction

Our scientific foundations are grounded on distributed collaborative systems supported by sophisticated data sharing mechanisms and on service oriented computing with an emphasis on orchestration and on non functional properties.

Distributed collaborative systems enable distributed group work supported by computer technologies. Designing such systems require an expertise in Distributed Systems and in Computer-supported collaborative activities research area. Besides theoretical and technical aspects of distributed systems, design of distributed collaborative systems must take into account the human factor to offer solutions suitable for users and groups. The SCORE team vision is to move away from a centralized authority based collaboration towards a decentralized collaboration where users have full control over their data that they can store locally and decide with whom to share them. The SCORE team investigates the issues related to the management of distributed shared data and coordination between users and groups.

Service oriented Computing [31] is an established domain on which the ECOO and now the SCORE team has been contributing for a long time. It refers to the general discipline that studies the development of computer applications on the web. A service is an independent software program with a specific functional context and capabilities published as a service contract (or more traditionally an API). A service composition aggregates a set of services and coordinates their interactions. The scale, the autonomy of services, the heterogeneity and some design principles underlying Service Oriented Computing open new research questions that are at the basis of our research. They span the disciplines of distributed computing, software engineering and CSCW. Our approach to contribute to the general vision of Service Oriented Computing and more generally to the emerging discipline of Service Science has been and is still to focus on the question of the efficient and flexible construction of reliable and secure high level services through the coordination/orchestration/composition of other services provided by distributed organizations or people.

3.2. Consistency Models for Distributed Collaborative Systems

Collaborative systems are distributed systems that allow users to share data. One important issue is to manage consistency of shared data according to concurrent access. Traditional consistency criteria such as locking, serializability, linearizability are not adequate for collaborative systems.

Causality, Convergence and Intention preservation (CCI) [34] are more suitable for developing middleware for collaborative applications.

We develop algorithms for ensuring CCI properties on collaborative distributed systems. Constraints on the algorithms are different according to the type of distributed system and type of data. The distributed system can be centralized, decentralized or peer-to-peer. The type of data can include strings, growable arrays, ordered trees, semantic graphs and multimedia data.

3.3. Optimistic Replication

Replication of data among different nodes of a network allows improving reliability, fault-tolerance, and availability. When data are mutable, consistency among the different replicas must be ensured. Pessimistic replication is based on the principle of single-copy consistency while optimistic replication allows the replicas to diverge during a short time period. The consistency model for optimistic replication [33] is called eventual consistency, meaning that replicas are guaranteed to converge to the same value when the system is idle.

Our research focuses on the two most promising families of optimistic replication algorithms for ensuring CCI:

- the operational transformation (OT) algorithms [29]
- the algorithms based on commutative replicated data types (CRDT) [32].

Operational transformation algorithms are based on the application of a transformation function when a remote modification is integrated into the local document. Integration algorithms are generic, being parametrized by operational transformation functions which depend on replicated document types. The advantage of these algorithms is their genericity. These algorithms can be applied to any data type and they can merge heterogeneous data in a uniform manner.

Commutative replicated data types is a new class of algorithms initiated by WOOT [30] a first algorithm designed WithOut Operational Transformations. They ensure consistency of highly dynamic content on peer-to-peer networks. Unlike traditional optimistic replication algorithms, they can ensure consistency without concurrency control. CRDT algorithms rely on natively commutative operations defined on abstract data types such as lists or ordered trees. Thus, they do not require a merge algorithm or an integration procedure.

3.4. Business Process Management

Business Process Management (BPM) is considered as a core discipline behind Service Management and Computing. BPM, that includes the analysis, the modelling, the execution, the monitoring and the continuous improvement of enterprise processes is for us a central domain of studies.

A lot of efforts has been devoted in the past years to establish standard business process models founded on well grounded theories (e.g. Petri Nets) that meet the needs of both business analysts but also of software engineers and software integrators. This has lead to heated debate as both points of view are very difficult to reconciliate between the analyst side and the IT side. On one side, the business people in general require models that are easy to use and understand and that can be quickly adapted to exceptional situations. On the other side, IT people need models with an operational semantic in order to be able transform them into executable artefacts. Part of our work has been an attempt to reconcile these point of views, leading on one side to the Bonita product and more recently on our work in crisis management where the same people are designing, executing and monitoring the process as it executes. But more generally, and at a larger scale, we have been considering the problem of process spanning the barriers of organisations. This leads us to consider the more general problem of service composition as a way to coordinate inter organisational construction of applications providing value based on the composition of lower level services [28].

3.5. Service Composition

More and more, we are considering processes as pieces of software whose execution traverse the boundaries of organisations. This is especially true with service oriented computing where processes compose services produced by many organisations. We tackle this problem from very different perspectives, trying to find the best compromise between the need for privacy of internal processes from organisations and the necessity to publicize large part of them, proposing to distribute the execution and the orchestration of processes among the organisations themselves, and attempting to ensure non-functional properties in this distributed setting [27].

Non functional aspects of service composition relate to all the properties and service agreements that one want to ensure and that are orthogonal to the actual business but that are important when a service is selected and integrated in a composition. This includes transactional context, security, privacy, and quality of service in general. Defining and orchestrating services on a large scale while providing the stakeholders with some strong guarantees on their execution is a first class problem for us. For a long time, we have proposed models and solutions to ensure that some properties (e.g. transactional properties) were guaranteed on process execution, either through design or through the definition of some protocols. Our work has also been extended to the problems of security, privacy and service level agreement among partners. These questions are still central in our work. Then, one major problem of current approaches is to monitor the execution of the compositions, integrating the distributed dimension. This problem can be tackled using event-based algorithms and techniques. Using our previous results an event oriented composition framework DISC, we have obtained new results dedicated to the runtime verification of violations in service choreographies.

ALGORILLE Project-Team

3. Research Program

3.1. Structuring Applications

Computing on different scales is a challenge under constant development that, almost by definition, will always try to reach the edge of what is possible at any given moment in time: in terms of the scale of the applications under consideration, in terms of the efficiency of implementations and in what concerns the optimized utilization of the resources that modern platforms provide or require. The complexity of all these aspects is currently increasing rapidly:

3.1.1. Diversity of platforms.

Design of processing hardware is diverging in many different directions. Nowadays we have SIMD registers inside processors, on-chip or off-chip accelerators (GPU, FPGA, vector-units), multi-cores and hyperthreading, multi-socket architectures, clusters, grids, clouds... The classical monolithic architecture of one-algorithm/one-implementation that solves a problem is obsolete in many cases. Algorithms (and the software that implements them) must deal with this variety of execution platforms robustly.

As we know, the “*free lunch*” for sequential algorithms provided by the increase of processor frequencies is over, we have to go parallel. But the “*free lunch*” is also over for many automatic or implicit adaption strategies between codes and platforms: e.g the best cache strategies can’t help applications that accesses memory randomly, or algorithms written for “simple” CPU (von Neumann model) have to be adapted substantially to run efficiently on vector units.

3.1.2. The communication bottleneck.

Communication and processing capacities evolve at a different pace, thus the *communication bottleneck* is always narrowing. An efficient data management is becoming more and more crucial.

Not many implicit data models have yet found their place in the HPC domain, because of a simple observation: latency issues easily kill the performance of such tools. In the best case, they will be able to hide latency by doing some intelligent caching and delayed updating. But they can never hide the bottleneck for bandwidth.

HPC was previously able to cope with the communication bottleneck by using an explicit model of communication, namely MPI. It has the advantage of imposing explicit points in code where some guarantees about the state of data can be given. It has the clear disadvantage that coherence of data between different participants is difficult to manage and is completely left to the programmer.

Here, our approach is and will be to timely request explicit actions (like MPI) that mark the availability of (or need for) data. Such explicit actions ease the coordination between tasks (coherence management) and allow the platform underneath the program to perform a pro-active resource management.

3.1.3. Models of interdependence and consistency.

Interdependence of data between different tasks of an application and components of hardware will be crucial to ensure that developments will possibly scale on the ever diverging architectures. We have up to now presented such models (PRO, DHO, ORWL) and their implementations, and proved their validity for the context of SPMD-type algorithms.

Over the next years we will have to enlarge the spectrum of their application. On the algorithm side we will have to move to heterogeneous computations combining different types of tasks in one application. For the architectures we will have to take into account the fact of increased heterogeneity, processors of different speed, multi-cores, accelerators (FPU, GPU, vector units), communication links of different bandwidth and latency, memory and generally storage capacity of different size, speed and access characteristics. First implementations using ORWL in that context look particularly promising.

The models themselves will have to evolve to be better suited for more types of applications, such that they allow for a more fine-grained partial locking and access of objects. They should handle e.g collaborative editing or the modification of just some fields in a data structure. This work has already started with DHO which allows the locking of *data ranges* inside an object. But a more structured approach would certainly be necessary here to be usable more comfortably in applications.

3.1.4. Frequent IO.

A complete parallel application includes I/O of massive data, at an increasing frequency. In addition to applicative input and output data flow, I/O is used for checkpointing or to store traces of execution. These then can be used to restart in case of failure (hardware or software) or for a post-mortem analysis of a chain of computations that led to catastrophic actions (for example in finance or in industrial system control). The difficulty of frequent I/O is more pronounced on hierarchical parallel architectures that include accelerators with local memory.

I/O has to be included in the design of parallel programming models and tools. ORWL will be enriched with such tools and functionalities, in order to ease the modeling and development of parallel applications that include data IO, and to exploit most of the performance potential of parallel and distributed architectures.

3.1.5. Algorithmic paradigms.

Concerning asynchronous algorithms, we have developed several versions of implementations, allowing us to precisely study the impact of our design choices. However, we are still convinced that improvements are possible in order to extend its application domain, especially concerning the detection of global convergence and the control of asynchronism. We are currently working on the design of a generic and non-intrusive way of implementing such a procedure in any parallel iterative algorithm.

Also, we would like to compare other variants of asynchronous algorithms, such as waveform relaxations. Here, computations are not performed for each time step of the simulation but for an entire time interval. Then, the evolution of the elements at the frontiers between the domain that are associated to the processors are exchanged asynchronously. Although we have already studied such schemes in the past, we would like to see how they will behave on recent architectures, and how the models and software for data consistency mentioned above can be helpful in that context.

3.1.6. Cost models and accelerators.

We have already designed some models that relate computation power and energy consumption. Our next goal is to design and implement an auto-tuning system that controls the application according to user defined optimization criteria (computation and/or energy performance). This implies the insertion of multi-schemes and/or multi-kernels into the application such that it will able to adapt its behavior to the requirements.

3.2. Transparent Resource Management for Clouds.

Given the extremely large offer of resources by public or private clouds, users need software assistance to make provisioning decisions. Our goal is to design a **cloud resource broker** which handles the workload of a user or of a community of users as a multi-criteria optimization problem. The notions of resource usage, scheduling, provisioning and task management have been adapted to this new context. For example, to minimize the makespan of a DAG of tasks, usually a fixed number of resources is assumed. On IaaS clouds, the amount of resources can be provisioned at any time, and hence the scheduling problem must be redefined using one new prevalent optimization criterion: the financial cost of the computation.

3.2.1. Provisioning strategies.

the provisioning strategies are hence central to the broker. They are designed after heuristics which aim to fit execution constraints and satisfy user preferences. For instance, lowering the costs can be achieved with strategies aiming at reusing already leased resources, or switch to less powerful and cheaper resources. However, some economic models proposed by cloud providers involve a complex cost-benefit analysis which we plan to address. Moreover, these economic models incur additional costs, e.g for data storage or transfer, which have to be taken into account to design a comprehensive broker.

3.2.2. User workload analysis.

Another possible extension of the capability of such a broker is the analysis of user workloads. Characterizing the workload might help to anticipate the behavior of each alternative provisioning strategy. The objective is to allow the user to select the suitable provisioning solution thanks to concrete information, such as completion time and financial cost.

3.2.3. Simulation of cloud platforms.

Providing concrete information about provisioning solutions can also be achieved through simulation. Although predicting the behavior of applicative cases in real grid environment is made very difficult by the shared (e.g multi-tenant), heterogeneous and dynamic nature of the resources, cloud resources (i.e. VMs) are perceived as reserved and homogeneous and stable by the end-user. Therefore, proposing an accurate prediction of the different strategies through an accurate simulation process would be a strong decision support for the user.

3.3. Experimental methodologies for the evaluation of distributed systems

Distributed systems are very challenging to study, test, and evaluate. Computer scientists traditionally prefer to study their systems *a priori* by reasoning theoretically on the constituents and their interactions. But the complexity of large-scale distributed systems makes this methodology near to impossible, explaining that most of the studies are done *a posteriori* through experiments.

In AlGorille, we strive at designing a comprehensive set of solutions for experimentation on distributed systems by working on several methodologies (formal assessment, simulation, use of experimental facilities, emulation) and by leveraging the convergence opportunities between methodologies (co-development, shared interfaces, validation combining several methodologies).

3.3.1. Simulation and dynamic verification

Our team plays a key role in the SimGrid project, a mature simulation toolkit widely used in the distributed computing community. Since more than ten years, we work on the validity, scalability and robustness of our tool.

We are currently extending the applicability to **Clouds and Exascale systems**. Therefore, we work toward disk and memory models in addition to the already existing network and CPU models. The tool's scalability and efficiency also constitutes a permanent concern to us. **Interfaces** constitute another important work axis, with the addition of specific APIs on top of our simulation kernel. They provide the "syntactic sugar" needed to express algorithms of these communities. For example, virtual machines are handled explicitly in the interface provided for Cloud studies. Similarly, we pursue our work on an implementation of the MPI standard allowing to study real applications using that interface. This work may also be extended in the future to other interfaces such as OpenMP or OpenCL.

We integrated a model checking kernel in SimGrid to enable **formal correctness studies** in addition to the practical performance studies enabled by simulation. Being able to study these two fundamental aspects of distributed applications within the same tool constitutes a major advantage for our users. In the future, we will enforce this capacity for the study of correctness and performance such that we hope to tackle their usage on real applications.

3.3.2. Experimentation on testbeds and production facilities, emulation

Our work in this research axis is meant to bring major contributions to the **industrialization of experimentation** on parallel and distributed systems. It is structured through multiple layers that range from the design of a testbed supporting high-quality experimentation, to the study of how stringent experimental methodology could be applied to our field, as depicted in Figure 2 .

During the last years, we have played a **key role in the design and development of Grid'5000** by leading the design and technical developments, and by managing several engineers working on the platform. We pursue our involvement in the design of the testbed with a focus on ensuring that the testbed provides all the features needed for high-quality experimentation. We also collaborate with other testbeds sharing similar goals in order to exchange ideas and views. We now work on **basic services supporting experimentation** such as resources verification, management of experimental environments, control of nodes, management of data, etc. Appropriate collaborations will ensure that existing solutions are adopted to the platform and improved as much as possible.

One key service for experimentation is the ability to alter experimental conditions using emulation. We work on the **Distem emulator**, focusing on its validation and on adding features (such as the ability to emulate faults, varying availability, churn, load injection, etc) and investigate if altering memory and disk performance is possible. Other goals are to scale the tool up to 20000 virtual nodes while improving the tool usability and documentation.

We work on **orchestration of experiments** in order to combine all the basic services mentioned previously in an efficient and scalable manner, with the design of a workflow-based experiment control engine named **XPFlow**.

3.3.3. *Convergence and co-design of experimental methodologies*

We see the experimental methodologies we work on as steps of a common experimental staircase: ideally, **one could and should leverage the various methodologies to address different facets of the same problem**. To facilitate that, we must co-design common or compatible formalisms, semantics and data formats.

Other experimental sciences such as biology and physics have paved the way in terms of scientific methodology. We **should learn from other experimental sciences, adopt good practices and adapt them** to Computer Science's specificities.

But Computer Science also has specific features that make it the ideal field to **create a truly Open Science**: provide infrastructure and tools for publishing and reproducing experiments and results, linked with our own methodologies and tools.

Finally, one important part of our work is to maintain a deep understanding of systems and their environments, in order to properly model them and experiment on them. Similarly, we need to understand the emerging scientific challenges in our field in order to improve adequately our experimental tools.

../../../../projets/algorille/IMG/explayers.png

Figure 2. General structure of our project: We plan to address all layers of the experimentation stack.

ALPINES Team

3. Research Program

3.1. Overview

The research described here is directly relevant to several steps of the numerical simulation chain. Given a numerical simulation that was expressed as a set of differential equations, our research focuses on mesh generation methods for parallel computation, novel numerical algorithms for linear algebra, as well as algorithms and tools for their efficient and scalable implementation on high performance computers. The validation and the exploitation of the results will be performed with collaborators from applications and it will be based on the usage of existing tools. In summary, the topics studied in our group are the following:

- Numerical methods and algorithms
  - Mesh generation for parallel computation
  - Solvers for numerical linear algebra
  - Computational kernels for numerical linear algebra
- Validation on numerical simulations

3.2. Domain specific language - parallel FreeFem++

In the engineering, researchers, and teachers communities, there is a strong demand for simulation frameworks that are simple to install and use, efficient, sustainable, and that solve efficiently and accurately complex problems for which there are no dedicated tools or codes available. In our group we develop FreeFem++ (see http://www.freefem.org/ff++), a user dedicated language for solving PDEs. The goal of FreeFem++ is not to be a substitute for complex numerical codes, but rather to provide an efficient and relatively generic tool for:

- getting a quick answer to a specific problem,
- prototype the resolution of a new complex problem.

The current users of FreeFem++ are mathematicians, engineers, university professors, and students. In general for these users the installation of public libraries as MPI, MUMPS, Ipopt, Blas, lapack, OpenGL, fftw, scotch, is a very difficult problem. For this reason, the authors of FreeFem++ have created a user friendly language, and over years have enriched its capabilities and provided tools for compiling FreeFem++ such that the users do not need to have special knowledge of computer science. This leads to an important work on porting the software on different emerging architectures.

Today, the main components of parallel FreeFem++ are:

1. definition of a coarse grid,
2. splitting of the coarse grid,
3. mesh generation of all subdomains of the coarse grid, and construction of parallel datat structures for vectors and sparse matrices from the mesh of the subdomain,
4. call to a linear solver,
5. analysis of the result.

All these components are parallel, except for point (5) which is not in the focus of our research. However for the moment, the parallel mesh generation algorithm is very simple and not sufficient, for example it addresses only polygonal geometries. Having a better parallel mesh generation algorithm is one of the goals of our project. In addition, in the current version of FreeFem++, the parallelism is not hidden from the user, it is done through direct calls to MPI. Our goal is also to hide all the MPI calls in the specific language part of FreeFem++.

3.3. Solvers for numerical linear algebra

Iterative methods are widely used in industrial applications, and preconditioning is the most important research subject here. Our research considers domain decomposition methods and iterative methods and its goal is to develop solvers that are suitable for parallelism and that exploit the fact that the matrices are arising from the discretization of a system of PDEs on unstructured grids.

One of the main challenges that we address is the lack of robustness and scalability of existing methods as incomplete LU factorizations or Schwarz-based approaches, for which the number of iterations increases significantly with the problem size or with the number of processors. This is often due to the presence of several low frequency modes that hinder the convergence of the iterative method. To address this problem, we study direction preserving solvers in the context of multilevel domain decomposition methods with adaptive coarse spaces and multilevel incomplete decompositions. A judicious choice for the directions to be preserved through filtering or low rank approximations allows us to alleviate the effect of low frequency modes on the convergence.

We also focus on developing boundary integral equation methods that would be adapted to the simulation of wave propagation in complex physical situations, and that would lend themselves to the use of parallel architectures, which includes devising adapted domain decomposition approaches. The final objective is to bring the state of the art on boundary integral equations closer to contemporary industrial needs.

3.4. Computational kernels for numerical linear algebra

The design of new numerical methods that are robust and that have well proven convergence properties is one of the challenges addressed in Alpines. Another important challenge is the design of parallel algorithms for the novel numerical methods and the underlying building blocks from numerical linear algebra. The goal is to enable their efficient execution on a diverse set of node architectures and their scaling to emerging high-performance clusters with an increasing number of nodes.

Increased communication cost is one of the main challenges in high performance computing that we address in our research by investigating algorithms that minimize communication, as communication avoiding algorithms. We propose to integrate the minimization of communication into the algorithmic design of numerical linear algebra problems. This is different from previous approaches where the communication problem was addressed as a scheduling or as a tuning problem. The communication avoiding algorithmic design is an aproach originally developed in our group since 2007 (initially in collaboration with researchers from UC Berkeley and CU Denver). While at mid term we focus on reducing communication in numerical linear algebra, at long term we aim at considering the communication problem one level higher, during the parallel mesh generation tool described earlier.

AVALON Team

3. Research Program

3.1. Energy Application Profiling and Modelization

International roadmaps schedule to build exascale systems by the 2018 time frame. According to the Top500 list published in November 2013, the most powerful supercomputer is the Tianhe-2 platform, a machine with more than 3,000,000 cores. It consumes more than 17 MW for a maximum performance of 33 PFlops while the Defense Advanced Research Projects Agency (DARPA) has set to 20 MW the maximum energy consumption of an exascale supercomputer [59].

Energy efficiency is therefore a major challenge for building next generation large scale platforms. The targeted platforms will gather hundreds of million cores, low power servers, or CPUs. Besides being very important, their power consumption will be dynamic and irregular.

Thus, to consume energy efficiently, we aim at investigating two research directions. First, we need to improve the measure, the understanding, and the analysis of the large-scale platform energy consumption. Unlike approaches [60] that mix the usage of internal and external wattmeters on a small set of resources, we target high frequency and precise internal and external energy measurements of each physical and virtual resources on large scale distributed systems.

Secondly, we need to find new mechanisms that consume less and better on such platforms. Combined with hardware optimizations, several works based on shutdown or slowdown approaches aim at reducing energy consumption of distributed platforms and applications. To consume less, we first plan to explore the provision of accurate estimation of the energy consumed by applications without pre-executing and knowing them while most of the works try to do it based on in-depth application knowledge (code instrumentation [64], phase detection for specific HPC applications [69], etc.). As a second step, we aim at designing a framework model that allows interactions, dialogues and decisions taken in cooperation between the user/application, the administrator, the resource manager, and the energy supplier. While smart grid is one of the last killer scenarios for networks, electrical provisioning of next generation large IT infrastructures remains a challenge.

3.2. Data-intensive Application Profiling, Modeling, and Management

Recently, the term “Big Data” has emerged to design data sets or collections so large that they become intractable for classical tools. This term is most of the time implicitly linked to “analytics” to refer to issues such as curation, storage, search, sharing, analysis, and visualization. However, the Big Data challenge is not limited to data-analytics, a field that is well covered by programming languages and run-time systems such as Map-Reduce. It also encompasses data-intensive applications. These applications can be sorted into two categories. In High Performance Computing (HPC), data-intensive applications leverage post-petascale infrastructures to perform highly parallel computations on large amount of data, while in High Throughput Computing (HTC), a large amount of independent and sequential computations are performed on huge data collections.

These two types of data-intensive applications (HTC and HPC) raise challenges related to profiling and modeling that the Avalon team proposes to address. While the characteristics of data-intensive applications are very different, our work will remain coherent and focused. Indeed, a common goal will be to acquire a better understanding of both the applications and the underlying infrastructures running them to propose the best match between application requirements and infrastructure capacities. To achieve this objective, we will extensively rely on logging and profiling in order to design sound, accurate, and validated models. Then, the proposed models will be integrated and consolidated within a single simulation framework (SIMGRID). This will allow us to explore various potential “what-if?” scenarios and offer objective indicators to select interesting infrastructure configurations that match application specificities.

Another challenge is the ability to mix several heterogeneous infrastructure that scientists have at their disposal (*e.g.,* Grids, Clouds and Desktop Grids) to execute data-intensive applications. Leveraging the aforementioned results, we will design strategies for efficient data management service for hybrid computing infrastructures.

3.3. Resourc-Agnostic Application Description Model

When programming in parallel, users expect to obtain performance improvement, whatever the cost is. For long, parallel machines have been simple enough to let a user program them given a minimal abstraction of their hardware. For example, MPI [63] exposes the number of nodes but hides the complexity of network topology behind a set of collective operations; OpenMP [67] simplifies the management of threads on top of a shared memory machine while OpenACC [66] aims at simplifying the use of GPGPU.

However, machines and applications are getting more and more complex so that the cost of manually handling an application is becoming very high [61]. Hardware complexity also stems from the unclear path towards next generations of hardware coming from the frequency wall: multi-core CPU, many-core CPU, GPGPUs, deep memory hierarchy, etc. have a strong impact on parallel algorithms. Hence, even though an abstract enough parallel language (UPC, Fortress, X10, etc.) succeeds, it will still face the challenge of supporting distinct codes corresponding to different algorithms corresponding to distinct hardware capacities.

Therefore, the challenge we aim to address is to define a model, for describing the structure of parallel and distributed applications that enables code variations but also efficient executions on parallel and distributed infrastructures. Indeed, this issue appears for HPC applications but also for cloud oriented applications. The challenge is to adapt an application to user constraints such as performance, energy, security, etc.

Our approach is to consider component based models [70] as they offer the ability to manipulate the software architecture of an application. To achieve our goal, we consider a “compilation” approach that transforms a resource-agnostic application description into a resource-specific description. The challenge is thus to determine a component based model that enables to efficiently compute application mapping while being tractable. In particular, it has to provide an efficient support with respect to application and resource elasticity, energy consumption and data management.

3.4. Application Mapping and Scheduling

This research axis is at the crossroad of the Avalon team. In particular, it gathers results of the three others research axis. We plan to consider application mapping and scheduling through the following three issues.

3.4.1. Application Mapping and Software Deployment

Application mapping and software deployment consist in the process of assigning distributed pieces of software to a set of resources. Resources can be selected according to different criteria such as performance, cost, energy consumption, security management, etc. A first issue is to select resources at application launch time. With the wide adoption of elastic platforms, *i.e.,* platforms that let the number of resources allocated to an application to be increased or decreased during its execution, the issue is also to handle resource selection at runtime.

The challenge in this context corresponds to the mapping of applications onto distributed resources. It will consist in designing algorithms that in particular take into consideration application profiling, modeling, and description.

A particular facet of this challenge is propose scheduling algorithms for dynamic and elastic platforms. As the amount of elements can vary, some kind of control of the platforms must be used accordingly to the scheduling.

3.4.2. Non-Deterministic Workflow Scheduling

Many scientific applications are described through workflow structures. Due to the increasing level of parallelism offered by modern computing infrastructures, workflow applications now have to be composed not only of sequential programs, but also of parallel ones. New applications are now built upon workflows with conditionals and loops (also called non-deterministic workflows).

These workflows can not be scheduled beforehand. Moreover cloud platforms bring on-demand resource provisioning and pay-as-you-go billing models. Therefore, there is a problem of resource allocation for non-deterministic workflows under budget constraints and using such an elastic management of resources.

Another important issue is data management. We need to schedule the data movements and replications while taking job scheduling into account. If possible, data management and job scheduling should be done at the same time in a closely coupled interaction.

3.4.3. Security Management in Cloud Infrastructure

Security has been proven to be sometimes difficult to obtain [68] and several issues have been raised in Clouds. Nowadays virtualization is used as the sole mechanism to secure different users sharing resources on Clouds. But, due to improper virtualization of all the components of Clouds (such as micro-architectural components), data leak and modification can occur. Accordingly, next-generation protection mechanisms are required to enforce security on Clouds and provide a way to cope with the current limitation of virtualization mechanisms.

As we are dealing with parallel and distributed applications, security mechanisms must be able to cope with multiple machines. Our approach is to combine a set of existing and novel security mechanisms that are spread in the different layers and components of Clouds in order to provide an in-depth and end-to-end security on Clouds. To do it, our first challenge is to define a generic model to express security policies.

Our second challenge is to work on security-aware resource allocation algorithms. The goal of such algorithms is to find a good trade-off between security and unshared resources. Consequently, they can limit resources sharing to increase security. It leads to complex trade-off between infrastructure consolidation, performance, and security.

CEPAGE Project-Team

3. Research Program

3.1. Modeling Platform Dynamics

Modeling the platform dynamics in a satisfying manner, in order to design and analyze efficient algorithms, is a major challenge. In distributed platforms, the performance of individual nodes (be they computing or communication resources) will fluctuate; in a fully dynamic platform, the set of available nodes will also change over time, and algorithms must take these changes into account if they are to be efficient.

There are basically two ways one can model such evolution: one can use a *stochastic process*, or some kind of *adversary model*.

In a stochastic model, the platform evolution is governed by some specific probability distribution. One obvious advantage of such a model is that it can be simulated and, in many well-studied cases, analyzed in detail. The two main disadvantages are that it can be hard to determine how much of the resulting algorithm performance comes from the specifics of the evolution process, and that estimating how realistic a given model is – none of the current project participants are metrology experts.

In an adversary model, it is assumed that these unpredictable changes are under the control of an adversary whose goal is to interfere with the algorithms efficiency. Major assumptions on the system's behavior can be included in the form of restrictions on what this adversary can do (like maintaining such or such level of connectivity). Such models are typically more general than stochastic models, in that many stochastic models can be seen as a probabilistic specialization of a nondeterministic model (at least for bounded time intervals, and up to negligible probabilities of adopting "forbidden" behaviors).

Since we aim at proving guaranteed performance for our algorithms, we want to concentrate on suitably restricted adversary models. The main challenge in this direction is thus to describe sets of restricted behaviors that both capture realistic situations and make it possible to prove such guarantees.

3.2. Models for Platform Topology and Parameter Estimation

On the other hand, in order to establish complexity and approximation results, we also need to rely on a precise theoretical model of the targeted platforms.

- At a lower level, several models have been proposed to describe interference between several simultaneous communications. In the 1-port model, a node cannot simultaneously send to (and/or receive from) more than one node. Most of the “steady state” scheduling results have been obtained using this model. On the other hand, some authors propose to model incoming and outgoing communication from a node using fictitious incoming and outgoing links, whose bandwidths are fixed. The main advantage of this model, although it might be slightly less accurate, is that it does not require strong synchronization and that many scheduling problems can be expressed as multi-commodity flow problems, for which efficient decentralized algorithms are known. Another important issue is to model the bandwidth actually allocated to each communication when several communications compete for the same long-distance link.
- At a higher level, proving good approximation ratios on general graphs may be too difficult, and it has been observed that actual platforms often exhibit a simple structure. For instance, many real life networks satisfy small-world properties, and it has been proved, for instance, that greedy routing protocols on small world networks achieve good performance. It is therefore of interest to prove that logical (given by the interactions between hosts) and physical platforms (given by the network links) exhibit some structure in order to derive efficient algorithms.

3.3. General Framework for Validation

3.3.1. Low level modeling of communications

In the context of large scale dynamic platforms, it is unrealistic to determine precisely the actual topology and the contention of the underlying network at application level. Indeed, existing tools such as Alnem [114] are very much based on quasi-exhaustive determination of interferences, and it takes several days to determine the actual topology of a platform made up of a few tens of nodes. Given the dynamism of the platforms we target, we need to rely on less sophisticated models, whose parameters can be evaluated at runtime.

Therefore, we propose to model each node using a small set of parameters. This is related to the theoretical notion of distance labeling [103], and corresponds to assigning labels to the nodes, so that a cheap operation on the labels of two nodes provides an estimation of the value of a given parameter (the latency or the bandwidth between two nodes, for instance). Several solutions for performance estimation on the Internet are based on this notion, under the terminology of Network Coordinate Systems. Vivaldi [94], IDES [115] and Sequoia [117] are examples of such systems for latency estimation. In the case of bandwidth estimation, fewer solutions have been proposed. We have studied the last-mile model, in which we model each node by an incoming and an outgoing bandwidth and neglect interference that appears at the core of the network (Internet), in order to concentrate on local constraints.

3.3.2. Simulation

Once low level modeling has been obtained, it is crucial to be able to test the proposed algorithms. To do this, we will first rely on simulation rather than direct experimentation. Indeed, in order to be able to compare heuristics, it is necessary to execute those heuristics on the same platform. In particular, all changes in the topology or in the resource performance should occur at the same time during the execution of the different heuristics. In order to be able to replicate the same scenario several times, we need to rely on simulations. Moreover, a metric for providing approximation results in the case of dynamic platforms necessarily requires computing the optimal solution at each time step, which can be done off-line if all traces for the different resources are stored. Using simulation rather than experiments can be justified if the simulator itself has been proven valid. Moreover, the modeling of communications, processing and their interactions may be much more complex in the simulator than in the model used to provide a theoretical approximation ratio, such as in SimGrid. In particular, sophisticated TCP models for bandwidth sharing have been implemented in SimGRID.

During the course of the USS-SimGrid ANR Arpege project, the SimGrid simulation framework has been adapted to large scale environments. Thanks to hierarchical platform description, to simpler and more scalable network models, and to the possibility to distribute the simulation of several nodes, it is now possible to perform simulations of very large platforms (of the order of 10^5 resources). This work will be continued in the ANR SONGS project, which aims at making SimGrid usable for Next Generation Systems (P2P, Grids, Clouds, HPC). In this context, simulation of exascale systems are envisioned, and we plan to develop models for platform dynamicity to allow realistic and reproducible experimentation of our algorithms.

3.3.3. Practical validation and scaling

Finally, we propose several applications that will be described in detail in Section 5. These applications cover a large set of fields (molecular dynamics, continuous integration...). All these applications will be developed and tested with an academic or industrial partner. In all these collaborations, our goal is to prove that the services that we propose can be integrated as steering tools in already developed software. Our goal is to assert the practical interest of the services we develop and then to integrate and to distribute them as a library for large scale computing.

At a lower level, in order to validate the models we propose, i.e. make sure that the predictions given by the model are close enough to the actual values, we need realistic datasets of network performance on large scale distributed platforms. Latency measurements are easiest to perform, and several datasets are available to researchers and serve as benchmarks to the community. Bandwidth datasets are more difficult to obtain, because of the measurement cost. As part of the bedibe software (see section 5.4), we have implemented a script to perform such measurements on the Planet-Lab platform [83]. We plan to make these datasets available to the community so that they can be used as benchmarks to compare the different solutions proposed.

GRAND-LARGE Project-Team

3. Research Program

3.1. Large Scale Distributed Systems (LSDS)

What makes a fundamental difference between recent Global Computing systems (Seti@home), Grid (EGEE, TeraGrid) and former works on distributed systems is the large scale of these systems. This characteristic becomes also true for large scale parallel computers gathering tens of thousands of CPU cores. The notion of Large Scale is linked to a set of features that has to be taken into account in these systems. An example is the system dynamicity caused by node volatility: in Internet Computing Platforms (also called Desktop Grids), a non predictable number of nodes may leave the system at any time. Some recent results also report a very low MTTI (Mean Time To Interrupt) in top level supercomputers gathering 100,000+ CPU cores. Another example of characteristics is the complete lack of control of nodes connectivity. In Desktop Grid, we cannot assume that external administrator is able to intervene in the network setting of the nodes, especially their connection to Internet via NAT and Firewalls. This means that we have to deal with the in place infrastructure in terms of performance, heterogeneity, dynamicity and connectivity. These characteristics, associated with the requirement of scalability, establish a new research context in distributed systems. The Grand-Large project aims at investigating theoretically as well as experimentally the fundamental mechanisms of LSDS, especially for the high performance computing applications.

3.1.1. Computing on Large Scale Global Computing systems

Large scale parallel and distributed systems are mainly used in the context of Internet Computing. As a consequence, until Sept. 2007, Grand-Large has focused mainly on Desktop Grids. Desktop Grids are developed for computing (SETI@home, Folding@home, Decrypthon, etc.), file exchanges (Napster, Kazaa, eDonkey, Gnutella, etc.), networking experiments (PlanetLab, Porivo) and communications such as instant messaging and phone over IP (Jabber, Skype). In the High Performance Computing domain, LSDS have emerged while the community was considering clustering and hierarchical designs as good performance-cost tradeoffs. Nowadays, Internet Computing systems are still very popular (the BOINC platform is used to run over 40 Internet Computing projects and XtremWeb is used in production in three countries) and still raise important research issues.

Desktop Grid systems essentially extend the notion of computing beyond the frontier of administration domains. The very first paper discussing this type of systems [79] presented the Worm programs and several key ideas that are currently investigated in autonomous computing (self replication, migration, distributed coordination, etc.). LSDS inherit the principle of aggregating inexpensive, often already in place, resources, from past research in cycle stealing/resource sharing. Due to its high attractiveness, cycle stealing has been studied in many research projects like Condor [69] , Glunix [64] and Mosix [45], to cite a few. A first approach to cross administration domains was proposed by Web Computing projects such as Jet [73], Charlotte [46], Javeline [57], Bayanihan [77], SuperWeb [42], ParaWeb [52] and PopCorn [54]. These projects have emerged with Java, taking benefit of the virtual machine properties: high portability across heterogeneous hardware and OS, large diffusion of virtual machine in Web browsers and a strong security model associated with bytecode execution. Performance and functionality limitations are some of the fundamental motivations of the second generation of Global Computing systems like BOINC [44] and XtremWeb [60]. The second generation of Global Computing systems appeared in the form of generic middleware which allow scientists and programmers to design and set up their own distributed computing project. As a result, we have seen the emergence of large communities of volunteers and projects. Currently, Global Computing systems are among the largest distributed systems in the world. In the mean time, several studies succeeded to understand and enhance the performance of these systems, by characterizing the system resources in term of volatility and heterogeneity and by studying new scheduling heuristics to support new classes of applications: data-intensive, long running application with checkpoint, workflow, soft-real time etc... However, despite these recent progresses, one can note that Global Computing systems are not yet part of high performance solution, commonly used by scientists. Recent researches to fulfill the requirements of Desktop Grids for high demanding users aim at redesigning Desktop Grid middleware by essentially turning a set of volatile nodes into a virtual cluster and allowing the deployment of regular HPC utilities (batch schedulers, parallel communication libraries, checkpoint services, etc...) on top of this virtual cluster. The new generation would permit a better integration in the environment of the scientists such as computational Grids, and consequently, would broaden the usage of Desktop Grid.

The high performance potential of LSDS platforms has also raised a significant interest in the industry. Performance demanding users are also interested by these platforms, considering their cost-performance ratio which is even lower than the one of clusters. Thus, several Desktop Grid platforms are daily used in production in large companies in the domains of pharmacology, petroleum, aerospace, etc.

Desktop Grids share with Grid a common objective: to extend the size and accessibility of a computing infrastructure beyond the limit of a single administration domain. In [61], the authors present the similarities and differences between Grid and Global Computing systems. Two important distinguishing parameters are the user community (professional or not) and the resource ownership (who own the resources and who is using them). From the system architecture perspective, we consider two main differences: the system scale and the lack of control of the participating resources. These two aspects have many consequences, at least on the architecture of system components, the deployment methods, programming models, security (trust) and more generally on the theoretical properties achievable by the system.

Beside Desktop Grids and Grids, large scale parallel computers with tens of thousands (and even hundreds of thousands) of CPU cores are emerging with scalability issues similar to the one of Internet Computing systems: fault tolerance at large scale, large scale data movements, tools and languages. Grand-Large is gradually considering the application of selected research results, in the domain of large scale parallel computers, in particular for the fault tolerance and language topics.

3.1.2. Building a Large Scale Distributed System

This set of studies considers the XtremWeb project as the basis for research, development and experimentation. This LSDS middleware is already operational. This set gathers 4 studies aiming at improving the mechanisms and enlarging the functionalities of LSDS dedicated to computing. The first study considers the architecture of the resource discovery engine which, in principle, is close to an indexing system. The second study concerns the storage and movements of data between the participants of a LSDS. In the third study, we address the issue of scheduling in LSDS in the context of multiple users and applications. Finally the last study seeks to improve the performance and reduce the resource cost of the MPICH-V fault tolerant MPI for desktop grids.

3.1.2.1. The resource discovery engine

A multi-users/multi-applications LSDS for computing would be in principle very close to a P2P file sharing system such as Napster [78], Gnutella [78] and Kazaa [68], except that the shared resource is the CPUs instead of files. The scale and lack of control are common features of the two kinds of systems. Thus, it is likely that solutions sharing fundamental mechanisms will be adopted, such as lower level communication protocols, resource publishing, resource discovery and distributed coordination. As an example, recent P2P projects have proposed distributed indexing systems like CAN [75], CHORD [80], PASTRY [76] and TAPESTRY [84] that could be used for resource discovery in a LSDS dedicated to computing.

The resource discovery engine is composed of a publishing system and a discovery engine, which allow a client of the system to discover the participating nodes offering some desired services. Currently, there is as much resource discovery architectures as LSDS and P2P systems. The architecture of a resource discovery engine is derived from some expected features such as speed of research, speed of reconfiguration, volatility tolerance, anonymity, limited use of the network, matching between the topologies of the underlying network and the virtual overlay network.

This study focuses on the first objective: to build a highly reliable and stable overlay network supporting the higher level services. The overlay network must be robust enough to survive unexpected behaviors (like malicious behaviors) or failures of the underlying network. Unfortunately it is well known that under specific assumptions, a system cannot solve even simples tasks with malicious participants. So, we focus the study on designing overlay algorithms for transient failures. A transient failure accepts any kind of behavior from the system, for a limited time. When failures stop, the system will eventually provide its normal service again.

A traditional way to cope with transient failures are self-stabilizing systems [59]. Existing self-stabilizing algorithms use an underlying network that is not compatible with LSDS. They assume that processors know their list of neighbors, which does not fit the P2P requirements. Our work proposes a new model for designing self-stabilizing algorithms without making this assumption, then we design, prove and evaluate overlay networks self-stabilizing algorithms in this model.

3.1.2.2. Fault Tolerant MPI

MPICH-V is a research effort with theoretical studies, experimental evaluations and pragmatic implementations aiming to provide a MPI implementation based on MPICH [71], featuring multiple fault tolerant protocols.

There is a long history of research in fault tolerance for distributed systems. We can distinguish the automatic/transparent approach from the manual/user controlled approach. The first approach relies either on coordinated checkpointing (global snapshot) or uncoordinated checkpointing associated with message logging. A well known algorithm for the first approach has been proposed by Chandy and Lamport [56]. This algorithm requires restarting all processes even if only one process crashes. So it is believed not to scale well. Several strategies have been proposed for message logging: optimistic [82], pessimistic [43], causal [83]. Several optimizations have been studied for the three strategies. The general context of our study is high performance computing on large platforms. One of the most used programming environments for such platforms is MPI.

Within the MPICH-V project, we have developed and published several original fault tolerant protocols for MPI: MPICH-V1 [49], MPICH-V2 [50], MPICH-Vcausal, MPICH-Vcl [51], MPICH-Pcl. The two first protocols rely on uncoordinated checkpointing associated with either remote pessimistic message logging or sender based pessimistic message logging. We have demonstrated that MPICH-V2 outperforms MPICH-V1. MPICH-Vcl implements a coordinated checkpoint strategy (Chandy-Lamport) removing the need of message logging. MPICH-V2 and Vcl are concurrent protocols for large clusters. We have compared them considering a new parameter for evaluating the merits of fault tolerant protocols: the impact of the fault frequency on the performance. We have demonstrated that the stress of the checkpoint server is the fundamental source of performance differences between the two techniques. MPICH-Vcausal implements a causal message logging protocols, removing the need for waiting acknowledgement in contrary to MPICH-V2. MPICH-Pcl is a blocking implementation of the Vcl protocol. Under the considered experimental conditions, message logging becomes more relevant than coordinated checkpoint when the fault frequency reaches 1 fault every 4 hours, for a cluster of 100 nodes sharing a single checkpoint server, considering a data set of 1 GB on each node and a 100 Mb/s network.

Multiple important events arose from this research topic. A new open source implementation of the MPI-2 standard was born during the evolution of the MPICH-V project, namely OpenMPI. OpenMPI is the result of the alliance of many MPI projects in the USA, and we are working to port our fault tolerance algorithms both into OpenMPI and MPICH.

Grids becoming more popular and accessible than ever, parallel applications developers now consider them as possible targets for computing demanding applications. MPI being the de-facto standard for the programming of parallel applications, many projects of MPI for the Grid appeared these last years. We contribute to this new way of using MPI through a European Project in which we intend to grid-enable OpenMPI and provide new fault-tolerance approaches fitted for the grid.

When introducing Fault-Tolerance in MPI libraries, one of the most neglected component is the runtime environment. Indeed, the traditional approach consists in restarting the whole application and runtime environment in case of failure. A more efficient approach could be to implement a fault-tolerant runtime environment, capable of coping with failures at its level, thus avoiding the restart of this part of the application. The benefits would be a quicker restart time, and a better control of the application. However, in order to build a fault-tolerant runtime environment for MPI, new topologies, more connected, and more stable, must be integrated in the runtime environment.

For traditional parallel machines of large scale (like large scale clusters), we also continue our investigation of the various fault tolerance protocols, by designing, implementing and evaluating new protocols in the MPICH-V project.

3.2. Volatility and Reliability Processing

In a global computing application, users voluntarily lend the machines, during the period they don't use them. When they want to reuse the machines, it is essential to give them back immediately. We assume that there is no time for saving the state of the computation (for example because the user is shooting down is machine). Because the computer may not be available again, it is necessary to organize checkpoints. When the owner takes control of his machine, one must be able to continue the computation on another computer from a checkpoint as near as possible from the interrupted state.

The problems raised by this way of managing computations are numerous and difficult. They can be put into two categories: synchronization and repartition problems.

- Synchronization problems (example). Assume that the machine that is supposed to continue the computation is fixed and has a recent checkpoint. It would be easy to consider that this local checkpoint is a component of a global checkpoint and to simply rerun the computation. But on one hand the scalability and on the other hand the frequency of disconnections make the use of a global checkpoint totally unrealistic. Then the checkpoints have to be local and the problem of synchronizing the recovery machine with the application is raised.
- Repartition problems (example). As it is also unrealistic to wait for the computer to be available again before rerunning the interrupted application, one has to design a virtual machine organization, where a single virtual machine is implemented as several real ones. With too few real machines for a virtual one, one can produce starvation; with too many, the efficiency is not optimal. The good solution is certainly in a dynamic organization.

These types of problems are not new ([62]). They have been studied deeply and many algorithmic solutions and implementations are available. What is new here and makes these old solutions not usable is scalability. Any solution involving centralization is impossible to use in practice. Previous works validated on former networks can not be reused.

3.2.1. Reliability Processing

We voluntarily presented in a separate section the volatility problem because of its specificity both with respect to type of failures and to frequency of failures. But in a general manner, as any distributed system, a global computing system has to resist to a large set of failures, from crash failures to Byzantine failures, that are related to incorrect software or even malicious actions (unfortunately, this hypothesis has to be considered as shown by DECRYPTHON project or the use of erroneous clients in SETI@HOME project), with in between, transient failures such as loss of message duplication. On the other hand, failures related accidental or malicious memory corruptions have to be considered because they are directly related to the very nature of the Internet. Traditionally, two approaches (masking and non-masking) have been used to deal with reliability problems. A masking solution hides the failures to the user, while a non-masking one may let the user notice that failures occur. Here again, there exists a large literature on the subject (cf. [70], [81], [59] for surveys). Masking techniques, generally based on consensus, are not scalable because they systematically use generalized broadcasting. The self-stabilizing approach (a non-masking solution) is well adapted (specifically its time adaptive version, cf. [67], [66], [47], [48], [63]) for three main reasons:

1. Low overhead when stabilized. Once the system is stabilized, the overhead for maintaining correction is low because it only involves communications between neighbours.

2. Good adaptivity to the reliability level. Except when considering a system that is continuously under attacks, self-stabilization provides very satisfying solutions. The fact that during the stabilization phase, the correctness of the system is not necessarily satisfied is not a problem for many kinds of applications.
3. Lack of global administration of the system. A peer to peer system does not admit a centralized administrator that would be recognized by all components. A human intervention is thus not feasible and the system has to recover by itself from the failures of one or several components, that is precisely the feature of self-stabilizing systems.

We propose:

1. To study the reliability problems arising from a global computing system, and to design self-stabilizing solutions, with a special care for the overhead.
2. For problem that can be solved despite continuously unreliable environment (such as information retrieval in a network), to propose solutions that minimize the overhead in space and time resulting from the failures when they involve few components of the system.
3. For most critical modules, to study the possibility to use consensus based methods.
4. To build an adequate model for dealing with the trade-off between reliability and cost.

3.3. Parallel Programming on Peer-to-Peer Platforms (P5)

Several scientific applications, traditionally computed on classical parallel supercomputers, may now be adapted for geographically distributed heterogeneous resources. Large scale P2P systems are alternative computing facilities to solve grand challenge applications.

Peer-to-Peer computing paradigm for large scale scientific and engineering applications is emerging as a new potential solution for end-user scientists and engineers. We have to experiment and to evaluate such programming to be able to propose the larger possible virtualization of the underlying complexity for the end-user.

3.3.1. Large Scale Computational Sciences and Engineering

Parallel and distributed scientific application developments and resource managements in these environments are a new and complex undertaking. In scientific computation, the validity of calculations, the numerical stability, the choices of methods and software are depending of properties of each peer and its software and hardware environments; which are known only at run time and are non-deterministic. The research to obtain acceptable frameworks, methodologies, languages and tools to allow end-users to solve accurately their applications in this context is capital for the future of this programming paradigm.

GRID scientific and engineering computing exists already since more than a decade. Since the last few years, the scale of the problem sizes and the global complexity of the applications increase rapidly. The scientific simulation approach is now general in many scientific domains, in addition to theoretical and experimental aspects, often link to more classic methods. Several applications would be computed on world-spread networks of heterogeneous computers using some web-based Application Server Provider (ASP) dedicated to targeted scientific domains. New very strategic domains, such as Nanotechnologies, Climatology or Life Sciences, are in the forefront of these applications. The development in this very important domain and the leadership in many scientific domains will depend in a close future to the ability to experiment very large scale simulation on adequate systems [65]. The P2P scientific programming is a potential solution, which is based on existing computers and networks. The present scientific applications on such systems are only concerning problems which are mainly data independents: i.e. each peer does not communicate with the others.

P2P programming has to develop parallel programming paradigms which allow more complex dependencies between computing resources. This challenge is an important goal to be able to solve large scientific applications. The results would also be extrapolated toward future petascale heterogeneous hierarchically designed supercomputers.

3.3.2. Experimentations and Evaluations

We have followed two tracks. First, we did experiments on large P2P platforms in order to obtain a realistic evaluation of the performance we can expect. Second, we have set some hypothesis on peers, networks, and scheduling in order to have theoretical evaluations of the potential performance. Then, we have chosen a classical linear algebra method well-adapted to large granularity parallelism and asynchronous scheduling: the block Gauss-Jordan method to invert dense very large matrices. We have also chosen the calculation of one matrix polynomial, which generates computation schemes similar to many linear algebra iterative methods, well-adapted for very large sparse matrices. Thus, we were able to theoretically evaluate the potential throughput with respect to several parameters such as the matrix size and the multicast network speed.

Since the beginning of the evaluations, we experimented with those parallel methods on a few dozen peer XtremWeb P2P Platforms. We continue these experiments on larger platforms in order to compare these results to the theoretical ones. Then, we would be able to extrapolate and obtain potential performance for some scientific applications.

Recently, we also experimented several Krylov based method, such as the Lanczos and GMRES methods on several grids, such as a French-Japanese grid using hundred of PC in France and 4 clusters at the University of Tsukuba. We also experimented on GRID5000 the same methods. We currently use several middleware such as Xtremweb, OmniRPC and Condor. We also begin some experimentations on the Tsubame supercomputer in collaboration with the TITech (Tokyo Institute of Technologies) in order to compare our grid approaches and the High performance one on an hybrid supercomputer.

Experimentations and evaluation for several linear algebra methods for large matrices on P2P systems will always be developed all along the Grand Large project, to be able to confront the different results to the reality of the existing platforms.

As a challenge, we would like, in several months, to efficiently invert a dense matrix of size one million using a several thousand peer platform. We are already inverting very large dense matrices on Grid5000 but more efficient scheduler and a larger number of processors are required to this challenge.

Beyond the experimentations and the evaluations, we propose the basis of a methodology to efficiently program such platforms, which allow us to define languages, tools and interface for the end-user.

3.3.3. Languages, Tools and Interface

The underlying complexity of the Large Scale P2P programming has to be mainly virtualized for the end-user. We have to propose an interface between the end-user and the middleware which may extract the end-user expertise or propose an on-the-shelf general solution. Targeted applications concern very large scientific problems which have to be developed using component technologies and up-to-dated software technologies.

We introduced the YML framework and language which allows to describe dependencies between components. We introduced different classes of components, depending of the level of abstraction, which are associated with divers parts of the framework. A component catalogue is managed by an administrator and/or the end-users. Another catalogue is managed with respect to the experimental platform and the middleware criteria. A front-end part is completely independent of any middleware or testbed, and a back-end part is developed for each targeted middleware/platform couple. A YML scheduler is adapted for each of the targeted systems.

The YML framework and language propose a solution to develop scientific applications to P2P and GRID platform. An end-user can directly develop programs using this framework. Nevertheless, many end-users would prefer avoid programming at the component and dependency graph level. Then, an interface has to be proposed soon, using the YML framework. This interface may be dedicated to a special scientific domain to be able to focus on the end-user vocabulary and P2P programming knowledge. We plan to develop such version based on the YML framework and language. The first targeted scientific domain will be very large linear algebra for dense or sparse matrices.

3.4. Methodology for Large Scale Distributed Systems

Research in the context of LSDS involves understanding large scale phenomena from the theoretical point of view up to the experimental one under real life conditions.

One key aspects of the impact of large scale on LSDS is the emergence of phenomena which are not co-ordinated, intended or expected. These phenomena are the results of the combination of static and dynamic features of each component of LSDS: nodes (hardware, OS, workload, volatility), network (topology, congestion, fault), applications (algorithm, parameters, errors), users (behavior, number, friendly/aggressive).

Validating current and next generation of distributed systems targeting large-scale infrastructures is a complex task. Several methodologies are possible. However, experimental evaluations on real testbeds are unavoidable in the life-cycle of a distributed middleware prototype. In particular, performing such real experiments in a rigorous way requires to benchmark developed prototypes at larger and larger scales. Fulfilling this requirement is mandatory in order to fully observe and understand the behaviors of distributed systems. Such evaluations are indeed mandatory to validate (or not!) proposed models of these distributed systems, as well as to elaborate new models. Therefore, to enable an experimentally-driven approach for the design of next generation of large scale distributed systems, developing appropriate evaluation tools is an open challenge.

Fundamental aspects of LSDS as well as the development of middleware platforms are already existing in Grand-Large. Grand-Large aims at gathering several complementary techniques to study the impact of large scale in LSDS: observation tools, simulation, emulation and experimentation on real platforms.

3.4.1. Observation tools

Observation tools are mandatory to understand and extract the main influencing characteristics of a distributed system, especially at large scale. Observation tools produce data helping the design of many key mechanisms in a distributed system: fault tolerance, scheduling, etc. We pursue the objective of developing and deploying a large scale observation tool (XtremLab) capturing the behavior of thousands of nodes participating to popular Desktop Grid projects. The collected data will be stored, analyzed and used as reference in a simulator (SIMBOINC).

3.4.2. Tool for scalability evaluations

Several Grid and P2P systems simulators have been developed by other teams: SimGrid [55], GridSim [53], Briks [41]. All these simulators considers relatively small scale Grids. They have not been designed to scale and simulate 10 K to 100 K nodes. Other simulators have been designed for large multi-agents systems such as Swarm [72] but many of them considers synchronous systems where the system evolution is guided by phases. In the P2P field, ad hoc many simulators have been developed, mainly for routing in DHT. Emulation is another tool for experimenting systems and networks with a higher degree of realism. Compared to simulation, emulation can be used to study systems or networks 1 or 2 orders of magnitude smaller in terms of number of components. However, emulation runs the actual OS/middleware/applications on actual platform. Compared to real testbed, emulation considers conducting the experiments on a fully controlled platform where all static and dynamic parameters can be controlled and managed precisely. Another advantage of emulation over real testbed is the capacity to reproduce experimental conditions. Several implementations/configurations of the system components can be compared fairly by evaluating them under the similar static and dynamic conditions. Grand-Large is leading one of the largest Emulator project in Europe called Grid explorer (French funding). This project has built and used a 1K CPUs cluster as hardware platform and gathers 24 experiments of 80 researchers belonging to 13 different laboratories. Experiments concerned developing the emulator itself and use of the emulator to explore LSDS issues. In term of emulation tool, the main outcome of Grid explorer is the V-DS system, using virtualization techniques to fold a virtual distributed system 50 times larger than the actual execution platform. V-DS aims at discovering, understanding and managing implicit uncoordinated large scale phenomena. Grid Explorer is still in use within the Grid'5000 platform and serves the community of 400 users 7 days a week and 24h a day.

3.4.3. Real life testbeds: extreme realism

The study of actual performance and connectivity mechanisms of Desktop Grids needs some particular testbed where actual middleware and applications can be run under real scale and real life conditions. Grand-Large is developing DSL-Lab, an experimental platform distributed on 50 sites (actual home of the participants) and using the actual DSL network as the connection between the nodes. Running experiments over DSL-Lab put the piece of software to study under extremely realistic conditions in terms of connectivity (NAT, Firewalls), performance (node and network), performance symmetry (DSL Network is not symmetric), etc.

To investigate real distributed system at large scale (Grids, Desktop Grids, P2P systems), under real life conditions, only a real platform (featuring several thousands of nodes), running the actual distributed system can provide enough details to clearly understand the performance and technical limits of a piece of software. Grand-Large members are strongly involved (as Project Director) in the French Grid5000 project which intents to deploy an experimental Grid testbed for computer scientists. This testbed features about 4000 CPUs gathering the resources of about 9 clusters geographically distributed over France. The clusters will be connected by a high speed network (Renater 10G). Grand-Large is the leading team in Grid5000, chairing the steering committee. As the Principal Investigator of the project, Grand-Large has taken some strong design decisions that nowadays give a real added value of Grid5000 compared to all other existing Grids: reconfiguration and isolation. From these two features, Grid5000 provides the capability to reproduce experimental conditions and thus experimental results, which is the cornerstone of any scientific instrument.

3.5. High Performance Scientific Computing

This research is in the area of high performance scientific computing, and in particular in parallel matrix algorithms. This is a subject of crucial importance for numerical simulations as well as other scientific and industrial applications, in which linear algebra problems arise frequently. The modern numerical simulations coupled with ever growing and more powerful computational platforms have been a major driving force behind a progress in numerous areas as different as fundamental science, technical/technological applications, life sciences.

The main focus of this research is on the design of efficient, portable linear algebra algorithms, such that solving a large set of linear equations or a least squares problem. The characteristics of the matrices commonly encountered in this situations can vary significantly, as are the computational platforms used for the calculations. Nonetheless two common trends are easily discernible. First, the problems to solve are larger and larger, since the numerical simulations are using higher resolution. Second, the architecture of today's supercomputers is getting very complex, and so the developed algorithms need to be adapted to these new achitectures.

3.5.1. Communication avoiding algorithms for numerical linear algebra

Since 2007, we work on a novel approach to dense and sparse linear algebra algorithms, which aims at minimizing the communication, in terms of both its volume and a number of transferred messages. This research is motivated by technological trends showing an increasing communication cost. Its main goal is to reformulate and redesign linear algebra algorithms so that they are optimal in an amount of the communication they perform, while retaining the numerical stability. The work here involves both theoretical investigation and practical coding on diverse computational platforms. We refer to the new algorithms as *communication avoiding algorithms* [58] [10]. In our team we focus on communication avoiding algorithms for dense direct methods as well as sparse iterative methods.

The theoretical investigation focuses on identifying lower bounds on communication for different operations in linear algebra, where communication refers to data movement between processors in the parallel case, and to data movement between different levels of memory hierarchy in the sequential case. The lower bounds are used to study the existing algorithms, understand their communication bottlenecks, and design new algorithms that attain them.

This research focuses on the design of linear algebra algorithms that minimize the cost of communication. Communication costs include both latency and bandwidth, whether between processors on a parallel computer or between memory hierarchy levels on a sequential machine. The stability of the new algorithms represents an important part of this work.

3.5.2. Preconditioning techniques

Solving a sparse linear system of equations is the most time consuming operation at the heart of many scientific applications, and therefore it has received a lot of attention over the years. While direct methods are robust, they are often prohibitive because of their time and memory requirements. Iterative methods are widely used because of their limited memory requirements, but they need an efficient preconditioner to accelerate their convergence. In this direction of research we focus on preconditioning techniques for solving large sparse systems.

One of the main challenges that we address is the scalability of existing methods as incomplete LU factorizations or Schwarz-based approaches, for which the number of iterations increases significantly with the problem size or with the number of processors. This is often due to the presence of several low frequency modes that hinder the convergence of the iterative method. To address this problem, we study direction preserving solvers in the context of multilevel filtering LU decompositions. A judicious choice for the directions to be preserved through filtering allows us to alleviate the effect of low frequency modes on the convergence. While preconditioners and their scalability are studied by many other groups, our approach of direction preserving and filtering is studied in only very few other groups in the world (as Lawrence Livermore National Laboratory, Frankfurt University, Pennsylvania State University).

3.5.3. Fast linear algebra solvers based on randomization

Linear algebra calculations can be enhanced by statistical techniques in the case of a square linear system $Ax = b$ where A is a general or symmetric indefinite matrix [3]& [1]. Thanks to a random transformation of A, it is possible to avoid pivoting and then to reduce the amount of communication. Numerical experiments show that this randomization can be performed at a very affordable computational price while providing us with a satisfying accuracy when compared to partial pivoting. This random transformation called Partial Random Butterfly Transformation (PRBT) is optimized in terms of data storage and flops count. A PRBT solver for LU factorization (and for LDL^T factorization on multicore) has been developed. This solver takes advantage of the latest generation of hybrid multicore/GPU machines and gives better Gflop/s performance than existing factorization routines [19].

3.5.4. Sensitivity analysis of linear algebra problems

We derive closed formulas for the condition number of a linear function of the total least squares solution [4]. Given an over determined linear systems $Ax = b$, we show that this condition number can be computed using the singular values and the right singular vectors of $[A, b]$ and A. We also provide an upper bound that requires the computation of the largest and the smallest singular value of $[A, b]$ and the smallest singular value of A. In numerical experiments, we compare these values with condition estimates from the literature.

HIEPACS Project-Team

3. Research Program

3.1. Introduction

The methodological component of HIEPACS concerns the expertise for the design as well as the efficient and scalable implementation of highly parallel numerical algorithms to perform frontier simulations. In order to address these computational challenges a hierarchical organization of the research is considered. In this bottom-up approach, we first consider in Section 3.2 generic topics concerning high performance computational science. The activities described in this section are transversal to the overall project and its outcome will support all the other research activities at various levels in order to ensure the parallel scalability of the algorithms. The aim of this activity is not to study general purpose solution but rather to address these problems in close relation with specialists of the field in order to adapt and tune advanced approaches in our algorithmic designs. The next activity, described in Section 3.3 , is related to the study of parallel linear algebra techniques that currently appear as promising approaches to tackle huge problems on extreme scale platforms. We highlight the linear problems (linear systems or eigenproblems) because they are in many large scale applications the main computational intensive numerical kernels and often the main performance bottleneck. These parallel numerical techniques, which are involved in the IPL C2S@EXA, will be the basis of both academic and industrial collaborations, some are described in Section 4.1 , but will also be closely related to some functionalities developed in the parallel fast multipole activity described in Section 3.4 . Finally, as the accuracy of the physical models increases, there is a real need to go for parallel efficient algorithm implementation for multiphysics and multiscale modeling in particular in the context of code coupling. The challenges associated with this activity will be addressed in the framework of the activity described in Section 3.5 .

Currently, we have one major application (see Section 4.1) that is in material physics. We will contribute to all steps of the design of the parallel simulation tool. More precisely, our applied mathematics skill will contribute to the modelling, our advanced numerical schemes will help in the design and efficient software implementation for very large parallel multi-scale simulations. We also participate to a few co-design actions in close collaboration with some applicative groups. The objective of this activity is to instanciate our expertise in fields where they are critical for designing scalable simulation tools. We refer to Section 4.2 for a detailed description of these activities.

3.2. High-performance computing on next generation architectures

Participants: Emmanuel Agullo, Olivier Coulaud, Luc Giraud, Mathieu Faverge, Abdou Guermouche, Matías Hastaran, Andra Hugo, Xavier Lacoste, Guillaume Latu, Stojce Nakov, Florent Pruvost, Pierre Ramet, Jean Roman, Mawussi Zounon.

The research directions proposed in HIEPACS are strongly influenced by both the applications we are studying and the architectures that we target (i.e., massively parallel many-core architectures, ...). Our main goal is to study the methodology needed to efficiently exploit the new generation of high-performance computers with all the constraints that it induces. To achieve this high-performance with complex applications we have to study both algorithmic problems and the impact of the architectures on the algorithm design.

From the application point of view, the project will be interested in multiresolution, multiscale and hierarchical approaches which lead to multi-level parallelism schemes. This hierarchical parallelism approach is necessary to achieve good performance and high-scalability on modern massively parallel platforms. In this context, more specific algorithmic problems are very important to obtain high performance. Indeed, the kind of applications we are interested in are often based on data redistribution for example (e.g. code coupling applications). This well-known issue becomes very challenging with the increase of both the number of computational nodes and the amount of data. Thus, we have both to study new algorithms and to adapt the existing ones. In addition, some issues like task scheduling have to be restudied in this new context. It is important to note that the work done in this area will be applied for example in the context of code coupling (see Section 3.5).

Considering the complexity of modern architectures like massively parallel architectures or new generation heterogeneous multicore architectures, task scheduling becomes a challenging problem which is central to obtain a high efficiency. Of course, this work requires the use/design of scheduling algorithms and models specifically to tackle our target problems. This has to be done in collaboration with our colleagues from the scheduling community like for example O. Beaumont (Inria REALOPT Project-Team). It is important to note that this topic is strongly linked to the underlying programming model. Indeed, considering multicore architectures, it has appeared, in the last five years, that the best programming model is an approach mixing multi-threading within computational nodes and message passing between them. In the last five years, a lot of work has been developed in the high-performance computing community to understand what is critic to efficiently exploit massively multicore platforms that will appear in the near future. It appeared that the key for the performance is firstly the grain of computations. Indeed, in such platforms the grain of the parallelism must be small so that we can feed all the processors with a sufficient amount of work. It is thus very crucial for us to design new high performance tools for scientific computing in this new context. This will be developed in the context of our solvers, for example, to adapt to this new parallel scheme. Secondly, the larger the number of cores inside a node, the more complex the memory hierarchy. This remark impacts the behaviour of the algorithms within the node. Indeed, on this kind of platforms, NUMA effects will be more and more problematic. Thus, it is very important to study and design data-aware algorithms which take into account the affinity between computational threads and the data they access. This is particularly important in the context of our high-performance tools. Note that this work has to be based on an intelligent cooperative underlying run-time (like the tools developed by the Inria RUNTIME Project-Team) which allows a fine management of data distribution within a node.

Another very important issue concerns high-performance computing using "heterogeneous" resources within a computational node. Indeed, with the emergence of the `GPU` and the use of more specific co-processors, it is important for our algorithms to efficiently exploit these new kind of architectures. To adapt our algorithms and tools to these accelerators, we need to identify what can be done on the `GPU` for example and what cannot. Note that recent results in the field have shown the interest of using both regular cores and `GPU` to perform computations. Note also that in opposition to the case of the parallelism granularity needed by regular multicore architectures, `GPU` requires coarser grain parallelism. Thus, making both `GPU` and regular cores work all together will lead to two types of tasks in terms of granularity. This represents a challenging problem especially in terms of scheduling. From this perspective, we investigate new approaches for composing parallel applications within a runtime system for heterogeneous platforms.

The SOLHAR project aims at studying and designing algorithms and parallel programming models for implementing direct methods for the solution of sparse linear systems on emerging computers equipped with accelerators. Several attempts have been made to accomplish the porting of these methods on such architectures; the proposed approaches are mostly based on a simple offloading of some computational tasks (the coarsest grained ones) to the accelerators and rely on fine hand-tuning of the code and accurate performance modeling to achieve efficiency. SOLHAR proposes an innovative approach which relies on the efficiency and portability of runtime systems, such as the `StarPU` tool developed in the RUNTIME team. Although the SOLHAR project will focus on heterogeneous computers equipped with GPUs due to their wide availability and affordable cost, the research accomplished on algorithms, methods and programming models will be readily applicable to other accelerator devices. Our final goal would be to have high performance solvers and tools which can efficiently run on all these types of complex architectures by exploiting all the resources of the platform (even if they are heterogeneous).

In order to achieve an advanced knowledge concerning the design of efficient computational kernels to be used on our high performance algorithms and codes, we will develop research activities first on regular frameworks before extending them to more irregular and complex situations. In particular, we will work first on optimized dense linear algebra kernels and we will use them in our more complicated direct and hybrid solvers for sparse linear algebra and in our fast multipole algorithms for interaction computations. In this context, we will participate to the development of those kernels in collaboration with groups specialized in dense linear algebra. In particular, we intend develop a strong collaboration with the group of Jack Dongarra at the University of Tennessee and collaborating research groups. The objectives will be to develop dense linear algebra algorithms and libraries for multicore architectures in the context the PLASMA project and for GPU and hybrid multicore/GPU architectures in the context of the MAGMA project. The framework that hosts all these research activities is the associated team MORSE.

A more prospective objective is to study the fault tolerance in the context of large-scale scientific applications for massively parallel architectures. Indeed, with the increase of the number of computational cores per node, the probability of a hardware crash on a core is dramatically increased. This represents a crucial problem that needs to be addressed. However, we will only study it at the algorithmic/application level even if it needed lower-level mechanisms (at OS level or even hardware level). Of course, this work can be done at lower levels (at operating system) level for example but we do believe that handling faults at the application level provides more knowledge about what has to be done (at application level we know what is critical and what is not). The approach that we will follow will be based on the use of a combination of fault-tolerant implementations of the run-time environments we use (like for example FT-MPI) and an adaptation of our algorithms to try to manage this kind of faults. This topic represents a very long range objective which needs to be addressed to guaranty the robustness of our solvers and applications. In that respect, we are involved in a ANR-Blanc project entitles RESCUE jointly with two other Inria EPI, namely ROMA and GRAND-LARGE and the G8 ESC international initiative. The main objective of the RESCUE project is to develop new algorithmic techniques and software tools to solve the exascale resilience problem. Solving this problem implies a departure from current approaches, and calls for yet-to-be- discovered algorithms, protocols and software tools.

Finally, it is important to note that the main goal of HIEPACS is to design tools and algorithms that will be used within complex simulation frameworks on next-generation parallel machines. Thus, we intend with our partners to use the proposed approach in complex scientific codes and to validate them within very large scale simulations.

3.3. High performance solvers for large linear algebra problems

Participants: Emmanuel Agullo, Astrid Casadei, Olivier Coulaud, Mathieu Faverge, Romain Garnier, Luc Giraud, Abdou Guermouche, Andra Hugo, Pablo Salas Medina, Stojce Nakov, Julien Pedron, Florent Pruvost, Pierre Ramet, Jean Roman, Xavier Vasseur.

Starting with the developments of basic linear algebra kernels tuned for various classes of computers, a significant knowledge on the basic concepts for implementations on high-performance scientific computers has been accumulated. Further knowledge has been acquired through the design of more sophisticated linear algebra algorithms fully exploiting those basic intensive computational kernels. In that context, we still look at the development of new computing platforms and their associated programming tools. This enables us to identify the possible bottlenecks of new computer architectures (memory path, various level of caches, inter processor or node network) and to propose ways to overcome them in algorithmic design. With the goal of designing efficient scalable linear algebra solvers for large scale applications, various tracks will be followed in order to investigate different complementary approaches. Sparse direct solvers have been for years the methods of choice for solving linear systems of equations, it is nowadays admitted that classical approaches are not scalable neither from a computational complexity nor from a memory view point for large problems such as those arising from the discretization of large 3D PDE problems. We will continue to work on sparse direct solvers on one hand to make sure they fully benefit from most advanced computing platforms on the other hand because they are a key building boxes for the design of some of our parallel algorithms such as the hybrid solvers described in the sequel of this section. Our activities in that context will mainly address preconditioned Krylov subspace methods; both components, preconditioner and Krylov solvers, will be investigated. In this framework, and possibly in relation with the research activity on fast multipole, we intend to study how emerging H-matrix arithmetic can benefit to our solver research efforts.

3.3.1. Parallel sparse direct solver

Solving large sparse systems $Ax = b$ of linear equations is a crucial and time-consuming step, arising in many scientific and engineering applications. Consequently, many parallel techniques for sparse matrix factorization have been studied and implemented.

Sparse direct solvers are mandatory when the linear system is very ill-conditioned; such a situation is often encountered in structural mechanics codes, for example. Therefore, to obtain an industrial software tool that must be robust and versatile, high-performance sparse direct solvers are mandatory, and parallelism is then necessary for reasons of memory capability and acceptable solution time. Moreover, in order to solve efficiently 3D problems with more than 50 million unknowns, which is now a reachable challenge with new multicore supercomputers, we must achieve good scalability in time and control memory overhead. Solving a sparse linear system by a direct method is generally a highly irregular problem that induces some challenging algorithmic problems and requires a sophisticated implementation scheme in order to fully exploit the capabilities of modern supercomputers.

New supercomputers incorporate many microprocessors which include themselves one or many computational cores. These new architectures induce strongly hierarchical topologies. These are called NUMA architectures. In the context of distributed NUMA architectures, in collaboration with the Inria RUNTIME team, we study optimization strategies to improve the scheduling of communications, threads and I/O. We have developed dynamic scheduling designed for NUMA architectures in the PaStiX solver. The data structures of the solver, as well as the patterns of communication have been modified to meet the needs of these architectures and dynamic scheduling. We are also interested in the dynamic adaptation of the computation grain to use efficiently multi-core architectures and shared memory. Experiments on several numerical test cases have been performed to prove the efficiency of the approach on different architectures.

In collaboration with the ICL team from the University of Tennessee, and the RUNTIME team from Inria, we are evaluating the way to replace the embedded scheduling driver of the PaStiX solver by one of the generic frameworks, PaRSEC or StarPU, to execute the task graph corresponding to a sparse factorization. The aims is to design algorithms and parallel programming models for implementing direct methods for the solution of sparse linear systems on emerging computer equipped with GPU accelerators. More generally, this work will be performed in the context of the ANR SOLHAR project which aims at designing high performance sparse direct solvers for modern heterogeneous systems. The project involves several groups working either on the sparse linear solver aspects (HIEPACS and ROMA from Inria and APO from IRIT), on runtime systems (RUNTIME from Inria) or scheduling algorithms (REALOPT and ROMA from Inria). The results of these efforts will be validated in the applications provided by the industrial project members, namely CEA-CESTA and EADS-IW.

On the numerical side, we are studying how the data sparsness that might exist in some dense blocks appearing during the factorization can be exploited using different compression techniques based on H-matrix (and variants) arithmetics. This research activity will be conducted in the framework of the FASTLA associate team and will naturally irrigate the hybrid solvers described below as well as closely interact with the other research efforts where similar data sparsness might be exploited.

3.3.2. Hybrid direct/iterative solvers based on algebraic domain decomposition techniques

One route to the parallel scalable solution of large sparse linear systems in parallel scientific computing is the use of hybrid methods that hierarchically combine direct and iterative methods. These techniques inherit the advantages of each approach, namely the limited amount of memory and natural parallelization for the iterative component and the numerical robustness of the direct part. The general underlying ideas are not new since they have been intensively used to design domain decomposition techniques; those approaches cover a fairly large range of computing techniques for the numerical solution of partial differential equations (PDEs) in time and space. Generally speaking, it refers to the splitting of the computational domain into sub-domains with or without overlap. The splitting strategy is generally governed by various constraints/objectives but the main one is to express parallelism. The numerical properties of the PDEs to be solved are usually intensively exploited at the continuous or discrete levels to design the numerical algorithms so that the resulting specialized technique will only work for the class of linear systems associated with the targeted PDE.

In that context, we intend to continue our effort on the design of algebraic non-overlapping domain decomposition techniques that rely on the solution of a Schur complement system defined on the interface introduced by the partitioning of the adjacency graph of the sparse matrix associated with the linear system. Although it is better conditioned than the original system the Schur complement needs to be precondition to be amenable to a solution using a Krylov subspace method. Different hierarchical preconditioners will be considered, possibly multilevel, to improve the numerical behaviour of the current approaches implemented in our software libraries HIPS and MaPHyS. In addition to this numerical studies, advanced parallel implementation will be developed that will involve close collaborations between the hybrid and sparse direct activities. In particular some additional work to complete the initial study conducted with CEA-CESTA on full multigrid method will be undertaken. This activity will be developed either in the framework of the CEA-Inria agreement and/or through joint work with bresilian colleagues within the HOSCAR initiative.

3.3.3. Linear Krylov solvers

preconditioning is the main focus of the two activities described above. They aim at speeding up the convergence of a Krylov subspace method that is the complementary component involved in the solvers of interest for us. In that framework, we believe that various aspects deserve to be investigated; we will consider the following ones:

- preconditioned block Krylov solvers for multiple right-hand sides. In many large scientific and industrial applications, one has to solve a sequence of linear systems with several right-hand sides given simultaneously or in sequence (radar cross section calculation in electromagnetism, various source locations in seismic, parametric studies in general, ...). For “simultaneous" right-hand sides, the solvers of choice have been for years based on matrix factorizations as the factorization is performed once and simple and cheap block forward/backward substitutions are then performed. In order to effectively propose alternative to such solvers, we need to have efficient preconditioned Krylov subspace solvers. In that framework, block Krylov approaches, where the Krylov spaces associated with each right-hand side are shared to enlarge the search space will be considered. They are not only attractive because of this numerical feature (larger search space), but also from an implementation point of view. Their block-structures exhibit nice features with respect to data locality and re-usability that comply with the memory constraint of multicore architectures. Following the initial work by J. Yan Fei during his post-doc in HIEPACS, we will continue the numerical study of the block GMRES variant that combine inexact break-down detection and deflation at restart. In addition a special attention will be paid to situations where a massive number of right-hand sides are given where variants exploiting the possible sparsness (i.e., compression using H-matrix arithmetic) of these right-hand sides will be explored to design efficient numerical algorithms. Beyond new numerical investigations, a software implementation to be included in our linear solver libray will be developed.

  For right-hand sides available one after each other, various strategies that exploit the information available in the sequence of Krylov spaces (e.g. spectral information) will be considered that include for instance technique to perform incremental update of the preconditioner or to built augmented Krylov subspaces.

- Extension or modification of Krylov subspace algorithms for multicore architectures: finally to match as much as possible to the computer architecture evolution and get as much as possible performance out of the computer, a particular attention will be paid to adapt, extend or develop numerical schemes that comply with the efficiency constraints associated with the available computers. Nowadays, multicore architectures seem to become widely used, where memory latency and bandwidth are the main bottlenecks; investigations on communication avoiding techniques will be undertaken in the framework of preconditioned Krylov subspace solvers as a general guideline for all the items mentioned above. This research activity will benefit from the starting FP7 EXA2CT project led by HIEPACS on behalf of the IPL C2S@EXA that involves two other Inria projects namely ALPINES and SAGE.

3.3.4. Eigensolvers

Many eigensolvers also rely on Krylov subspace techniques. Naturally some links exist between the Krylov subspace linear solvers and the Krylov subspace eigensolvers. We plan to study the computation of eigenvalue problems with respect to the following two different axes:

- Exploiting the link between Krylov subspace methods for linear system solution and eigensolvers, we intend to develop advanced iterative linear methods based on Krylov subspace methods that use some spectral information to build part of a subspace to be recycled, either though space augmentation or through preconditioner update. This spectral information may correspond to a certain part of the spectrum of the original large matrix or to some approximations of the eigenvalues obtained by solving a reduced eigenproblem. This technique will also be investigated in the framework of block Krylov subspace methods.
- In the context of the calculation of the ground state of an atomistic system, eigenvalue computation is a critical step; more accurate and more efficient parallel and scalable eigensolvers are required.

3.4. High performance Fast Multipole Method for N-body problems

Participants: Emmanuel Agullo, Bérenger Bramas, Arnaud Etcheverry, Olivier Coulaud, Matthias Messner, Cyrille Piacibello, Guillaume Sylvand.

In most scientific computing applications considered nowadays as computational challenges (like biological and material systems, astrophysics or electromagnetism), the introduction of hierarchical methods based on an octree structure has dramatically reduced the amount of computation needed to simulate those systems for a given accuracy. For instance, in the N-body problem arising from these application fields, we must compute all pairwise interactions among N objects (particles, lines, ...) at every timestep. Among these methods, the Fast Multipole Method (FMM) developed for gravitational potentials in astrophysics and for electrostatic (coulombic) potentials in molecular simulations solves this N-body problem for any given precision with $O(N)$ runtime complexity against $O(N^2)$ for the direct computation.

The potential field is decomposed in a near field part, directly computed, and a far field part approximated thanks to multipole and local expansions. We introduced a matrix formulation of the FMM that exploits the cache hierarchy on a processor through the Basic Linear Algebra Subprograms (BLAS). Moreover, we developed a parallel adaptive version of the FMM algorithm for heterogeneous particle distributions, which is very efficient on parallel clusters of SMP nodes. Finally on such computers, we developed the first hybrid MPI-thread algorithm, which enables to reach better parallel efficiency and better memory scalability. We plan to work on the following points in HIEPACS.

3.4.1. Improvement of calculation efficiency

Nowadays, the high performance computing community is examining alternative architectures that address the limitations of modern cache-based designs. GPU (Graphics Processing Units) and the Cell processor have thus already been used in astrophysics and in molecular dynamics. The Fast Mutipole Method has also been implemented on GPU. We intend to examine the potential of using these forthcoming processors as a building block for high-end parallel computing in N-body calculations. More precisely, we want to take advantage of our specific underlying BLAS routines to obtain an efficient and easily portable FMM for these new architectures. Algorithmic issues such as dynamic load balancing among heterogeneous cores will also have to be solved in order to gather all the available computation power. This research action will be conduced on close connection with the activity described in Section 3.2 .

3.4.2. Non uniform distributions

In many applications arising from material physics or astrophysics, the distribution of the data is highly non uniform and the data can grow between two time steps. As mentioned previously, we have proposed a hybrid MPI-thread algorithm to exploit the data locality within each node. We plan to further improve the load balancing for highly non uniform particle distributions with small computation grain thanks to dynamic load balancing at the thread level and thanks to a load balancing correction over several simulation time steps at the process level.

3.4.3. Fast multipole method for dislocation operators

The engine that we develop will be extended to new potentials arising from material physics such as those used in dislocation simulations. The interaction between dislocations is long ranged ($O(1/r)$) and anisotropic, leading to severe computational challenges for large-scale simulations. Several approaches based on the FMM or based on spatial decomposition in boxes are proposed to speed-up the computation. In dislocation codes, the calculation of the interaction forces between dislocations is still the most CPU time consuming. This computation has to be improved to obtain faster and more accurate simulations. Moreover, in such simulations, the number of dislocations grows while the phenomenon occurs and these dislocations are not uniformly distributed in the domain. This means that strategies to dynamically balance the computational load are crucial to achieve high performance.

3.4.4. Fast multipole method for boundary element methods

The boundary element method (BEM) is a well known solution of boundary value problems appearing in various fields of physics. With this approach, we only have to solve an integral equation on the boundary. This implies an interaction that decreases in space, but results in the solution of a dense linear system with $O(N^3)$ complexity. The FMM calculation that performs the matrix-vector product enables the use of Krylov subspace methods. Based on the parallel data distribution of the underlying octree implemented to perform the FMM, parallel preconditioners can be designed that exploit the local interaction matrices computed at the finest level of the octree. This research action will be conduced on close connection with the activity described in Section 3.3 . Following our earlier experience, we plan to first consider approximate inverse preconditionners that can efficiently exploit these data structures.

3.5. Efficient algorithmic for load balancing and code coupling in complex simulations

Participants: Astrid Casadei, Olivier Coulaud, Aurélien Esnard, Maria Predari, Pierre Ramet, Jean Roman, Clément Vuchener.

Many important physical phenomena in material physics and climatology are inherently complex applications. They often use multi-physics or multi-scale approaches, that couple different models and codes. The key idea is to reuse available legacy codes through a coupling framework instead of merging them into a standalone application. There is typically one model per different scale or physics; and each model is implemented by a parallel code. For instance, to model a crack propagation, one uses a molecular dynamic code to represent the atomistic scale and an elasticity code using a finite element method to represent the continuum scale. Indeed, fully microscopic simulations of most domains of interest are not computationally feasible. Combining such different scales or physics are still a challenge to reach high performance and scalability. If the model aspects are often well studied, there are several open algorithmic problems, that we plan to investigate in the HiePACS project-team.

3.5.1. Efficient schemes for multiscale simulations

As mentioned previously, many important physical phenomena, such as material deformation and failure (see Section 4.1), are inherently multiscale processes that cannot always be modeled via continuum model. Fully microscopic simulations of most domains of interest are not computationally feasible. Therefore, researchers must look at multiscale methods that couple micro models and macro models. Combining different scales such as quantum-atomistic or atomistic, mesoscale and continuum, are still a challenge to obtain efficient and accurate schemes that efficiently and effectively exchange information between the different scales. We are currently involved in two national research projects, that focus on multiscale schemes. More precisely, the models that we start to study are the quantum to atomic coupling (QM/MM coupling) in the ANR NOSSI and the atomic to dislocation coupling in the ANR OPTIDIS.

3.5.2. Dynamic load balancing for massively parallel coupled codes

In this context of code coupling, one crucial issue is undoubtedly the load balancing of the whole coupled simulation that remains an open question. The goal here is to find the best data distribution for the whole coupled simulation and not only for each standalone code, as it is most usually done. Indeed, the naive balancing of each code on its own can lead to an important imbalance and to a communication bottleneck during the coupling phase, that can drastically decrease the overall performance. Therefore, one argues that it is required to model the coupling itself in order to ensure a good scalability, especially when running on massively parallel architectures (tens of thousands of processors/cores). In other words, one must develop new algorithms and software implementation to perform a *coupling-aware* partitioning of the whole application.

Another related problem is the problem of resource allocation. This is particularly important for the global coupling efficiency and scalabilty, because each code involved in the coupling can be more or less computationally intensive, and there is a good trade-off to find between resources assigned to each code to avoid that one of them wait for the other(s). And what happens if the load of one code dynamically changes relatively to the other? In such a case, it could be convenient to dynamically adapt the number of resources used at runtime.

For instance, the conjugate heat transfer simulation in complex geometries (as developed by the CFD team of CERFACS) requires to couple a fluid/convection solver (AVBP) with a solid/conduction solver (AVTP). The AVBP code is much more CPU consuming than the AVTP code. As a consequence, there is an important computational imbalance between the two solvers. The use of new algorithms to correctly load balance coupled simulations with enhanced graph partitioning techniques appears as a promising way to reach better performances of coupled application on massively parallel computers.

3.5.3. Graph partitioning for hybrid solvers

Graph handling and partitioning play a central role in the activity described here but also in other numerical techniques detailed in Section 3.3 .

The Nested Dissection is now a well-known heuristic for sparse matrix ordering to both reduce the fill-in during numerical factorization and to maximize the number of independent computation tasks. By using the block data structure induced by the partition of separators of the original graph, very efficient parallel block solvers have been designed and implemented according to supernodal or multifrontal approaches. Considering hybrid methods mixing both direct and iterative solvers such as `HIPS` or `MaPHyS`, obtaining a domain decomposition leading to a good balancing of both the size of domain interiors and the size of interfaces is a key point for load balancing and efficiency in a parallel context. We intend to revisit some well-known graph partitioning techniques in the light of the hybrid solvers and design new algorithms to be tested in the `Scotch` package.

KERDATA Project-Team

3. Research Program

3.1. Our goals and methodology

Data-intensive applications demonstrate common requirements with respect to the need for data storage and I/O processing. These requirements lead to several core challenges discussed below.

Challenges related to cloud storage. In the area of cloud data management, a significant milestone is the emergence of the Map-Reduce [34] parallel programming paradigm, currently used on most cloud platforms, following the trend set up by Amazon [30]. At the core of Map-Reduce frameworks lies a key component, which must meet a series of specific requirements that have not fully been met yet by existing solutions: the ability to provide efficient *fine-grain access* to the files, while sustaining a *high throughput* in spite of *heavy access concurrency*. Additionally, as thousands of clients simultaneously access shared data, it is critical to preserve *fault-tolerance* and *security* requirements.

Challenges related to data-intensive HPC applications. The requirements exhibited by climate simulations specifically highlight a major, more general research topic. They have been clearly identified by international panels of experts like IESP [32] and EESI [31], in the context of HPC simulations running on post-Petascale supercomputers. A jump of one order of magnitude in the size of numerical simulations is required to address some of the fundamental questions in several communities such as climate modeling, solid earth sciences or astrophysics. In this context, the lack of data-intensive infrastructures and methodologies to analyze huge simulations is a growing limiting factor. The challenge is to find new ways to store and analyze massive outputs of data during and after the simulation without impacting the overall performance.

The overall goal of the KerData project-team is to bring a substantial contribution to the effort of the research community to address the above challenges. KerData aims to design and implement distributed algorithms for scalable data storage and input/output management for efficient large-scale data processing. We target two main execution infrastructures: cloud platforms and post-Petascale HPC supercomputers. We are also looking at other kinds of infrastructures (that we are considering as secondary), e.g. hybrid platforms combining enterprise desktop grids extended to cloud platforms. Our collaboration porfolio includes international teams that are active in this area both in Academia (e.g., Argonne National Lab, University of Illinois at Urbana-Champaign, University of Tsukuba) and Industry (Microsoft, IBM).

The highly experimental nature of our research validation methodology should be stressed. Our approach relies on building prototypes and on their large-scale experimental validation on real testbeds and experimental platforms. We strongly rely on the ALADDIN-Grid'5000 platform. Moreover, thanks to our projects and partnerships, we have access to reference software and physical infrastructures in the cloud area (Microsoft Azure, Amazon clouds, Nimbus clouds); in the post-Petascale HPC area we have access to the Jaguar and Kraken supercomputers (ranked 3rd and 11th respectively in the Top 500 supercomputer list) and to the Blue Waters supercomputer. This provides us with excellent opportunities to validate our results on realistic platforms.

Moreover, the consortiums of our current projects include application partners in the areas of Bio-Chemistry, Neurology and Genetics, and Climate Simulations. This is an additional asset, it enables us to take into account application requirements in the early design phase of our solutions, and to validate those solutions with real applications. We intend to continue increasing our collaborations with application communities, as we believe that this a key to perform effective research with a high potential impact.

3.2. Our research agenda

Three typical application scenarios are described in Section 4.1 :

- Joint genetic and neuroimaging data analysis on Azure clouds;
- Structural protein analysis on Nimbus clouds;
- I/O intensive climate simulations for the Blue Waters post-Petascale machine.

They illustrate the above challenges in some specific ways. They all exhibit a common scheme: massively concurrent processes which access massive data at a fine granularity, where data is shared and distributed at a large scale. To efficiently address the aforementioned challenges we have started to work out an approach called BlobSeer, which stands today at the center of our research efforts. This approach relies on the design and implementation of *scalable* distributed algorithms for data storage and access. They combine advanced techniques for decentralized metadata and data management, with versioning-based concurrency control to optimize the performance of applications under heavy access concurrency.

Preliminary experiments with our BlobSeer BLOB management system within today's cloud software infrastructures proved very promising. Recently, we used the BlobSeer approach as a starting point to address more in depth two usage scenarios, which led to two more specific approaches: 1) Pyramid (which borrows many concepts from BlobSeer), with a specific focus on array-oriented storage; and 2) Damaris (totally independent of BlobSeer), which exploits multicore parallelism in post-Petascale supercomputers. All these directions are described below.

Our short- and medium-term research plan is devoted to storage challenges in two main contexts: clouds and post-Petascale HPC architectures. Consequently, our research plan is split in two main themes, which correspond to their respective challenges. For each of those themes, we have initiated several actions through collaborative projects coordinated by KerData, which define our agenda for the next 4 years.

Based on very promising results demonstrated by BlobSeer in preliminary experiments [36], we have initiated several collaborative projects in the area of cloud data management, e.g., the MapReduce ANR project, the A-Brain Microsoft-Inria project, the Z-CloudFlow Microsoft-Inria project. Such frameworks are for us concrete and efficient means to work in close connection with strong partners already well positioned in the area of cloud computing research. Thanks to these projects, we have already started to enjoy a visible scientific positioning at the international level.

The particularly active Data@ExaScale Associate Team creates the framework for an enlarged research activity involving a large number of young researchers and students. It serves as a basis for extended research activities based on our approaches, carried out beyond the frontiers of our team. In the HPC area, our presence in the research activities of the Joint UIUC-Inria Lab for Petascale Computing at Urbana-Champaign is a very exciting opportunity that we have started to leverage. It facilitates high-quality collaborations and access to some of the most powerful supercomputers, an important asset which already helped us produce and transfer some results, as described in Section 6.4 .

MESCAL Project-Team

3. Research Program

3.1. Large System Modeling and Analysis

Participants: Bruno Gaujal, Arnaud Legrand, Panayotis Mertikopoulos, Florence Perronnin, Olivier Richard, Corinne Touati, Jean-Marc Vincent.

Markov chains, Queuing networks, Mean field approximation, Simulation, Performance evaluation, Discrete event dynamic systems.

3.1.1. Simulation of distributed systems

Since the advent of distributed computer systems, an active field of research has been the investigation of *scheduling* strategies for parallel applications. The common approach is to employ scheduling heuristics that approximate an optimal schedule. Unfortunately, it is often impossible to obtain analytical results to compare the efficiency of these heuristics. One possibility is to conduct large numbers of back-to-back experiments on real platforms. While this is possible on tightly-coupled platforms, it is unfeasible on modern distributed platforms (i.e., grids or peer-to-peer environments) as it is labor-intensive and does not enable repeatable results. The solution is to resort to *simulations*.

3.1.1.1. Flow Simulations

To make simulations of large systems efficient and trustful, we have used flow simulations (where streams of packets are abstracted into flows). SimGrid is a simulation platform that specifically targets the simulation of large distributed systems (grids, clusters, peer-to-peer systems, volunteer computing systems, clouds) from the perspective of applications. It enables to obtain repeatable results and to explore wide ranges of platform and application scenarios.

3.1.1.2. Perfect Simulation

Using a constructive representation of a Markovian queuing network based on events (often called GSMPs), we have designed perfect simulation algorithms computing samples distributed according to the stationary distribution of the Markov process with no bias. The tools based on our algorithms (ψ) can sample the stationary measure of Markov processes using directly the queuing network description. Some monotone networks with up to 10^{50} states can be handled within minutes over a regular PC.

3.1.2. Fluid models and mean field limits

When the size of systems grows very large, one may use asymptotic techniques to get a faithful estimate of their behavior. One such tool is mean field analysis and fluid limits, that can be used at a modeling and simulation level. Proving that large discrete dynamic systems can be approximated by continuous dynamics uses the theory of stochastic approximation pioneered by Michel Benaïm or population dynamics introduced by Thomas Kurtz and others. We have extended the stochastic approximation approach to take into account discontinuities in the dynamics as well as to tackle optimization issues.

Recent applications include call centers and peer to peer systems, where the mean field approach helps to get a better understanding of the behavior of the system and to solve several optimization problems. Another application concerns task brokering in desktop grids taking into account statistical features of tasks as well as of the availability of the processors. Mean field has also been applied to the performance evaluation of work stealing in large systems and to model central/local controllers as well as knitting systems.

3.1.3. Game Theory

Resources in large-scale distributed platforms (grid computing platforms, enterprise networks, peer-to-peer systems) are shared by a number of users having conflicting interests who are thus prone to act selfishly. A natural framework for studying such non-cooperative individual decision-making is game theory. In particular, game theory models the decentralized nature of decision-making.

It is well known that such non-cooperative behaviors can lead to important inefficiencies and unfairness. In other words, individual optimizations often result in global resource waste. In the context of game theory, a situation in which all users selfishly optimize their own utility is known as a *Nash equilibrium* or *Wardrop equilibrium*. In such equilibria, no user has interest in unilaterally deviating from its strategy. Such policies are thus very natural to seek in fully distributed systems and have some stability properties. However, a possible consequence is the *Braess paradox* in which the increase of resource happens at the expense of *every* user. This is why, the study of the occurrence and degree of such inefficiency is of crucial interest. Up until now, little is known about general conditions for optimality or degree of efficiency of these equilibria, in a general setting.

Many techniques have been developed to enforce some form of collaboration and improve these equilibria. In this context, it is generally prohibitive to take joint decisions so that a global optimization cannot be achieved. A possible option relies on the establishment of virtual prices, also called *shadow prices* in congestion networks. These prices ensure a rational use of resources. Equilibria can also be improved by advising policies to mobiles such that any user that does not follow these pieces of advice will necessarily penalize herself (*correlated equilibria*).

3.2. Management of Large Architectures

Participants: Arnaud Legrand, Olivier Richard, Corinne Touati.

Administration, Deployment, Peer-to-peer, Clusters, Grids, Clouds, Job scheduler

3.2.1. Instrumentation, analysis and prediction tools

To understand complex distributed systems, one has to provide reliable measurements together with accurate models before applying this understanding to improve system design.

Our approach for instrumentation of distributed systems (embedded systems as well as multi-core machines or distributed systems) relies on quality of service criteria. In particular, we focus on non-obtrusiveness and experimental reproducibility.

Our approach for analysis is to use statistical methods with experimental data of real systems to understand their normal or abnormal behavior. With that approach we are able to predict availability of very large systems (with more than 100,000 nodes), to design cost-aware resource management (based on mathematical modeling and performance evaluation of target architectures), and to propose several scheduling policies tailored for unreliable and shared resources.

3.2.2. Fairness in large-scale distributed systems

Large-scale distributed platforms (grid computing platforms, enterprise networks, peer-to-peer systems) result from the collaboration of many people. Thus, the scaling evolution we are facing is not only dealing with the amount of data and the number of computers but also with the number of users and the diversity of their behavior. In a high-performance computing framework, the rationale behind this joining of forces is that most users need a larger amount of resources than what they have on their own. Some only need these resources for a limited amount of time. On the opposite some others need as many resources as possible but do not have particular deadlines. Some may have mainly tightly-coupled applications while some others may have mostly embarrassingly parallel applications. The variety of user profiles makes resources sharing a challenge. However resources have to be *fairly* shared between users, otherwise users will leave the group and join another one. Large-scale systems therefore have a real need for fairness and this notion is missing from classical scheduling models.

3.2.3. Tools to operate clusters

The MESCAL project-team studies and develops a set of tools designed to help the installation and the use of a cluster of PCs. The first version had been developed for the Icluster1 platform exploitation. The main tools are a scalable tool for cloning nodes (KA-DEPLOY) and a parallel launcher based on the TAKTUK project (now developed by the MOAIS project-team). Many interesting issues have been raised by the use of the first versions among which we can mention environment deployment, robustness and batch scheduler integration. A second generation of these tools is thus under development to meet these requirements.

KA-DEPLOY has been retained as the primary deployment tool for the experimental national grid Grid'5000.

3.2.4. Simple and scalable batch scheduler for clusters and grids

Most known batch schedulers (PBS, LSF, Condor, ...) are of old-fashioned conception, built in a monolithic way, with the purpose of fulfilling most of the exploitation needs. This results in systems of high software complexity (150,000 lines of code for OpenPBS), offering a growing number of functions that are, most of the time, not used. In such a context, it becomes hard to control both the robustness and the scalability of the whole system.

OAR is an attempt to address these issues. Firstly, OAR is written in a very high level language (Perl) and makes intensive use of high level tools (MySql and TAKTUK), thereby resulting in a concise code (around 5000 lines of code) easy to maintain and extend. This small code as well as the choice of widespread tools (MySql) are essential elements that ensure a strong robustness of the system. Secondly, OAR makes use of SQL queries to perform most of its job management tasks thereby getting advantage of the strong scalability of most database management tools. Such scalability is further improved in OAR by making use of TAKTUK to manage nodes themselves.

3.3. Migration and resilience; Large scale data management

Participant: Yves Denneulin.

Fault tolerance, migration, distributed algorithms.

Most propositions to improve reliability address only a given application or service. This may be due to the fact that until clusters and intranet architectures arose, it was obvious that client and server nodes were independent. This is not the case in parallel scientific computing where a fault on a node can lead to a data loss on thousands of other nodes. The reliability of the system is hence a crucial point. MESCAL's work on this topic is based on the idea that each process in a parallel application will be executed by a group of nodes instead of a single node: when the node in charge of a process fails, another in the same group can replace it in a transparent way for the application.

There are two main problems to be solved in order to achieve this objective. The first one is the ability to migrate processes of a parallel, and thus communicating, application without enforcing modifications. The second one is the ability to maintain a group structure in a completely distributed way. The first one relies on a close interaction with the underlying operating systems and networks, since processes can be migrated in the middle of a communication. This can only be done by knowing how to save and replay later all ongoing communications, independently of the communication pattern. Freezing a process to restore it on another node is also an operation that requires collaboration of the operating system and a good knowledge of its internals. The other main problem (keeping a group structure) belongs to the distributed algorithms domain and is of a much higher level nature.

MOAIS Project-Team

3. Research Program

3.1. Scheduling

Participants: Pierre-François Dutot, Guillaume Huard, Grégory Mounié, Jean-Louis Roch, Denis Trystram, Frédéric Wagner.

The goal of this theme is to determine adequate multi-criteria objectives which are efficient (precision, reactivity, speed) and to study scheduling algorithms to reach these objectives.

In the context of parallel and distributed processing, the term *scheduling* is used with many acceptations. In general, scheduling means assigning tasks of a program (or processes) to the various components of a system (processors, communication links).

Researchers within MOAIS have been working on this subject for many years. They are known for their multiple contributions for determining the target dates and processors the tasks of a parallel program should be executed; especially regarding execution models (taking into account inter-task communications or any other system features) and the design of efficient algorithms (for which there exists a performance guarantee relative to the optimal scheduling).

Parallel tasks model and extensions. We have contributed to the definition and promotion of modern task models: parallel moldable tasks and divisible load. For both models, we have developed new techniques to derive efficient scheduling algorithms (with a good performance guaranty). We proposed recently some extensions taking into account machine unavailabilities (reservations).

Multi-objective Optimization. A natural question while designing practical scheduling algorithms is "which criterion should be optimized ?". Most existing works have been developed for minimizing the *makespan* (time of the latest tasks to be executed). This objective corresponds to a system administrator view who wants to be able to complete all the waiting jobs as soon as possible. The user, from his-her point of view, would be more interested in minimizing the average of the completion times (called *minsum*) of the whole set of submitted jobs. There exist several other objectives which may be pertinent for specific use. We worked on the problem of designing scheduling algorithms that optimize simultaneously several objectives with a theoretical guarantee on each objective. The main issue is that most of the policies are good for one criterion but bad for another one.
We have proposed an algorithm that is guaranteed for both *makespan* and *minsum*. This algorithm has been implemented for managing the resources of a cluster of the regional grid CIMENT. More recently, we extended such analysis to other objectives (makespan and reliability). We concentrate now on finding good algorithms able to schedule a set of jobs with a large variety of objectives simultaneously. For hard problems, we propose approximation of Pareto curves (best compromizes).

Incertainties. Most of the new execution supports are characterized by a higher complexity in predicting the parameters (high versatility in desktop grids, machine crash, communication congestion, cache effects, etc.). We studied some time ago the impact of incertainties on the scheduling algorithms. There are several ways for dealing with this problem: First, it is possible to design robust algorithms that can optimized a problem over a set of scenarii, another solution is to design flexible algorithms. Finally, we promote semi on-line approaches that start from an optimized off-line solution computed on an initial data set and updated during the execution on the "perturbed" data (stability analysis).

Game Theory. Game Theory is a framework that can be used for obtaining good solution of both previous problems (multi-objective optimization and incertain data). On the first hand, it can be used as a complement of multi-objective analysis. On the other hand, it can take into account the incertainties. We are curently working at formalizing the concept of cooperation.

Scheduling for optimizing parallel time and memory space. It is well known that parallel time and memory space are two antagonists criteria. However, for many scientific computations, the use of parallel architectures is motivated by increasing both the computation power and the memory space. Also, scheduling for optimizing both parallel time and memory space targets an important multicriteria objective. Based on the analysis of the dataflow related to the execution, we have proposed a scheduling algorithm with provable performance.

Coarse-grain scheduling of fine grain multithreaded computations on heterogeneous platforms. Designing multi-objective scheduling algorithms is a transversal problem. Work-stealing scheduling is well studied for fine grain multithreaded computations with a small critical time: the speed-up is asymptotically optimal. However, since the number of tasks to manage is huge, the control of the scheduling is expensive. We proposed a generalized lock-free cactus stack execution mechanism, to extend previous results, mainly from Cilk, based on the *work-first principle* for strict multi-threaded computations on SMPs to general multithreaded computations with dataflow dependencies. The main result is that optimizing the sequential local executions of tasks enables to amortize the overhead of scheduling. This distributed work-stealing scheduling algorithm has been implemented in **Kaapi**.

3.2. Adaptive Parallel and Distributed Algorithms Design

Participants: François Broquedis, Pierre-François Dutot, Thierry Gautier, Guillaume Huard, Bruno Raffin, Jean-Louis Roch, Denis Trystram, Frédéric Wagner.

This theme deals with the analysis and the design of algorithmic schemes that control (statically or dynamically) the grain of interactive applications.

The classical approach consists in setting in advance the number of processors for an application, the execution being limited to the use of these processors. This approach is restricted to a constant number of identical resources and for regular computations. To deal with irregularity (data and/or computations on the one hand; heterogeneous and/or dynamical resources on the other hand), an alternate approach consists in adapting the potential parallelism degree to the one suited to the resources. Two cases are distinguished:

- in the classical bottom-up approach, the application provides fine grain tasks; then those tasks are clustered to obtain a minimal parallel degree.
- the top-down approach (Cilk, Cilk+, TBB, Hood, Athapascan) is based on a work-stealing scheduling driven by idle resources. A local sequential depth-first execution of tasks is favored when recursive parallelism is available.

Ideally, a good parallel execution can be viewed as a flow of computations flowing through resources with no control overhead. To minimize control overhead, the application has to be adapted: a parallel algorithm on p resources is not efficient on $q < p$ resources. On one processor, the scheduler should execute a sequential algorithm instead of emulating a parallel one. Then, the scheduler should adapt to resource availability by changing its underlying algorithm. This first way of adapting granularity is implemented by Kaapi (default work-stealing schedule based on work-first principle).

However, this adaptation is restrictive. More generally, the algorithm should adapt itself at runtime to improve its performance by decreasing the overheads induced by parallelism, namely the arithmetic operations and communications. This motivates the development of new parallel algorithmic schemes that enable the scheduler to control the distribution between computation and communication (grain) in the application to find the good balance between parallelism and synchronizations. MOAIS has exhibited several techniques to manage adaptivity from an algorithmic point of view:

- amortization of the number of global synchronizations required in an iteration (for the evaluation of a stopping criterion);
- adaptive deployment of an application based on on-line discovery and performance measurements of communication links;
- generic recursive cascading of two kind of algorithms: a sequential one, to provide efficient executions on the local resource, and a parallel one that enables an idle resource to extract parallelism to dynamically suit the degree of parallelism to the available resources.

The generic underlying approach consists in finding a good mix of various algorithms, what is often called a "poly-algorithm". Particular instances of this approach are Atlas library (performance benchmark are used to decide at compile time the best block size and instruction interleaving for sequential matrix product) and FFTW library (at run time, the best recursive splitting of the FFT butterfly scheme is precomputed by dynamic programming). Both cases rely on pre-benchmarking of the algorithms. Our approach is more general in the sense that it also enables to tune the granularity at any time during execution. The objective is to develop processor oblivious algorithms: similarly to cache oblivious algorithms, we define a parallel algorithm as *processor-oblivious* if no program variable that depends on architecture parameters, such as the number or processors or their respective speeds, needs to be tuned to minimize the algorithm runtime.

We have applied this technique to develop processor oblivious algorithms for several applications with provable performance: iterated and prefix sum (partial sums) computations, stream computations (cipher and hd-video transformation), 3D image reconstruction (based on the concurrent usage of multi-core and GPU), loop computations with early termination.

By optimizing the work-stealing to our adaptive algorithm scheme, the non-blocking (wait-free) implementation of Kaapi has been designed and leads to the C library X-kaapi.

Extensions concern the development of algorithms that are both cache and processor oblivious on heterogeneous processors. The processor algorithms proposed for prefix sums and segmentation of an array are cache oblivious too.

3.3. Interactivity

Participants: Vincent Danjean, Pierre-François Dutot, Thierry Gautier, Bruno Raffin, Jean-Louis Roch.

The goal of this theme is to develop approaches to tackle interactivity in the context of large scale distributed applications.

We distinguish two types of interactions. A user can interact with an application having only little insight about the internal details of the program running. This is typically the case for a virtual reality application where the user just manipulates 3D objects. We have a "user-in-the-loop". In opposite, we have an "expert -in-the-loop" if the user is an expert that knows the limits of the progam that is being executed and that he can interacts with it to steer the execution. This is the case for instance when the user can change some parameters during the execution to improve the convergence of a computation.

3.3.1. User-in-the-loop

Some applications, like virtual reality applications, must comply with interactivity constraints. The user should be able to observe and interact with the application with an acceptable reaction delay. To reach this goal the user is often ready to accept a lower level of details. To execute such application on a distributed architecture requires to balance the workload and activation frequency of the different tasks. The goal is to optimize CPU and network resource use to get as close as possible to the reactivity/level of detail the user expect.

Virtual reality environments significantly improve the quality of the interaction by providing advanced interfaces. The display surface provided by multiple projectors in CAVE -like systems for instance, allows a high resolution rendering on a large surface. Stereoscopic visualization gives an information of depth. Sound and haptic systems (force feedback) can provide extra information in addition to visualized data. However driving such an environment requires an important computation power and raises difficult issues of synchronization to maintain the overall application coherent while guaranteeing a good latency, bandwidth (or refresh rate) and level of details. We define the coherency as the fact that the information provided to the different user senses at a given moment are related to the same simulated time.

Today's availability of high performance commodity components including networks, CPUs as well as graphics or sound cards make it possible to build large clusters or grid environments providing the necessary resources to enlarge the class of applications that can aspire to an interactive execution. However the approaches usually used for mid size parallel machines are not adapted. Typically, there exist two different approaches to handle data exchange between the processes (or threads). The synchronous (or FIFO) approach ensures all messages sent are received in the order they were sent. In this case, a process cannot compute a new state if all incoming buffers do not store at least one message each. As a consequence, the application refresh rate is driven by the slowest process. This can be improved if the user knows the relative speed of each module and specify a read frequency on each of the incoming buffers. This approach ensures a strong coherency but impact on latency. This is the approach commonly used to ensure the global coherency of the images displayed in multi-projector environments.The other approach, the asynchronous one, comes from sampling systems. The producer updates data in a shared buffer asynchronously read by the consumer. Some updates may be lost if the consumer is slower than the producer. The process refresh rates are therefore totally independent. Latency is improved as produced data are consumed as soon as possible, but no coherency is ensured. This approach is commonly used when coupling haptic and visualization systems. A fine tuning of the application usually leads to satisfactory results where the user does not experience major incoherences. However, in both cases, increasing the number of computing nodes quickly makes infeasible hand tuning to keep coherency and good performance.

We propose to develop techniques to manage a distributed interactive application regarding the following criteria :

- latency (the application reactivity);
- refresh rate (the application continuity);
- coherency (between the different components);
- level of detail (the precision of computations).

We developed a programming environment, called FlowVR, that enables the expression and realization of loosen but controlled coherency policies between data flows. The goal is to give users the possibility to express a large variety of coherency policies from a strong coherency based on a synchronous approach to an uncontrolled coherency based on an asynchronous approach. It enables the user to loosen coherency where it is acceptable, to improve asynchronism and thus performance. This approach maximizes the refresh rate and minimizes the latency given the coherency policy and a fixed level of details. It still requires the user to tune many parameters. In a second step, we are planning to explore auto-adaptive techniques that enable to decrease the number of parameters that must be user tuned. The goal is to take into account (possibly dynamically) user specified high level parameters like target latencies, bandwidths and levels of details, and to have the system automatically adapt to reach a trade-off given the user wishes and the resources available. Issues include multi-criterion optimizations, adaptive algorithmic schemes, distributed decision making, global stability and balance of the regulation effort.

3.3.2. Expert-in-the-loop

Some applications can be interactively guided by an expert who may give advices or answer specific questions to hasten a problem resolution. A theoretical framework has been developed in the last decade to define precisely the complexity of a problem when interactions with an expert is allowed. We are studying these interactive proof systems and interactive complexity classes in order to define efficient interactive algorithms dedicated to scheduling problems. This, in particular, applies to load-balancing of interactive simulations when a user interaction can generate a sudden surge of imbalance which could be easily predicted by an operator.

3.4. Adaptive middleware for code coupling and data movements

Participants: François Broquedis, Vincent Danjean, Thierry Gautier, Clément Pernet, Bruno Raffin, Jean-Louis Roch, Frédéric Wagner.

This theme deals with the design and implementation of programming interfaces in order to achieve an efficient coupling of distributed components.

The implementation of interactive simulation application requires to assemble together various software components and to ensure a semantic on the displayed result. To take into account functional aspects of the computation (inputs, outputs) as well as non functional aspects (bandwidth, latency, persistence), elementary actions (method invocation, communication) have to be coordinated in order to meet some performance objective (precision, quality, fluidity, *etc*). In such a context the scheduling algorithm plays an important role to adapt the computational power of a cluster architecture to the dynamic behavior due to the interactivity. Whatever the scheduling algorithm is, it is fundamental to enable the control of the simulation. The purpose of this research theme is to specify the semantics of the operators that perform components assembling and to develop a prototype to experiment our proposals on real architectures and applications.

3.4.1. Application Programming Interface

The specification of an API to compose interactive simulation application requires to characterize the components and the interaction between components.The respect of causality between elementary events ensures, at the application level, that a reader will see the *last* write with respect to an order. Such a consistency should be defined at the level of the application to control the events ordered by a chain of causality. For instance, one of the result of Athapascan was to prove that a data flow consistency is more efficient than other ones because it generates fewer messages. Beyond causality based interactions, new models of interaction should be studied to capture non predictable events (delay of communication, capture of image) while ensuring a semantic.

Our methodology is based on the characterization of interactions required between components in the context of an interactive simulation application. For instance, criteria could be coherency of visualization, degree of interactivity. Beyond such characterization we hope to provide an operational semantic of interactions (at least well suited and understood by usage) and a cost model. Moreover they should be preserved by composition to predict the cost of an execution for part of the application.

The main result relies on a computable representation of the future of an execution; representations such as macro data flow are well suited because they explicit which data are required by a task. Such a representation can be built at runtime by an interpretation technique: the execution of a function call is differed by computing beforehand at runtime a graph of tasks that represents the (future) calls to execute.

3.4.2. Kernel for Asynchronous, Adaptive, Parallel and Interactive Application

Managing the complexity related to fine grain components and reaching high efficiency on a cluster architecture require to consider a dynamic behavior. Also, the runtime kernel is based on a representation of the execution: data flow graph with attributes for each node and efficient operators will be the basis for our software. This kernel has to be specialized for the considered applications. The low layer of the kernel has features to transfer data and to perform remote signalization efficiently. Well known techniques and legacy code have to be reused. For instance, multithreading, asynchronous invocation, overlapping of latency by computing, parallel communication and parallel algorithms for collective operations are fundamental techniques to reach performance. Because the choice of the scheduling algorithm depends on the application and the architecture, the kernel will provide an *causally connected representation* of the system that is running. This allows to specialize the computation of a good schedule of the data flow graph by providing algorithms (scheduling algorithms for instance) that compute on this (causally connected) representation: any modification of the representation is turned into a modification on the system (the parallel program under execution). Moreover, the kernel provides a set of basic operators to manipulate the graph (*e.g.* computes a partition from a schedule, remapping tasks, ...) to allow to control a distributed execution.

ROMA Team

3. Research Program

3.1. Algorithms for probabilistic environments

There are two main research directions under this research theme. In the first one, we consider the problem of the efficient execution of applications in a failure-prone environment. Here, probability distributions are used to describe the potential behavior of computing platforms, namely when hardware components are subject to faults. In the second research direction, probability distributions are used to describe the characteristics and behavior of applications.

3.1.1. Application resilience

An application is resilient if it can successfully produce a correct result in spite of potential faults in the underlying system. Application resilience can involve a broad range of techniques, including fault prediction, error detection, error containment, error correction, checkpointing, replication, migration, recovery, etc. Faults are quite frequent in the most powerful existing supercomputers. The Jaguar platform, which ranked third in the TOP 500 list in November 2011 [67], had an average of 2.33 faults per day during the period from August 2008 to February 2010 [91]. The mean-time between faults of a platform is inversely proportional to its number of components. Progresses will certainly be made in the coming years with respect to the reliability of individual components. However, designing and building high-reliability hardware components is far more expensive than using lower reliability top-of-the-shelf components. Furthermore, low-power components may not be available with high-reliability. Therefore, it is feared that the progresses in reliability will far from compensate the steady projected increase of the number of components in the largest supercomputers. Already, application failures have a huge computational cost. In 2008, the DARPA white paper on "System resilience at extreme scale" [66] stated that high-end systems wasted 20% of their computing capacity on application failure and recovery.

In such a context, any application using a significant fraction of a supercomputer and running for a significant amount of time will have to use some fault-tolerance solution. It would indeed be unacceptable for an application failure to destroy centuries of CPU-time (some of the simulations run on the Blue Waters platform consumed more than 2,700 years of core computing time [62] and lasted over 60 hours; the most time-consuming simulations of the US Department of Energy (DoE) run for weeks to months on the most powerful existing platforms [65]).

Our research on resilience follows two different directions. On the one hand we design new resilience solutions, either generic fault-tolerance solutions or algorithm-based solutions. On the other hand we model and theoretically analyze the performance of existing and future solutions, in order to tune their usage and help determine which solution to use in which context.

3.1.2. Scheduling strategies for applications with a probabilistic behavior

Static scheduling algorithms are algorithms where all decisions are taken before the start of the application execution. On the contrary, in non-static algorithms, decisions may depend on events that happen during the execution. Static scheduling algorithms are known to be superior to dynamic and system-oriented approaches in stable frameworks [72], [78], [79], [90], that is, when all characteristics of platforms and applications are perfectly known, known a priori, and do not evolve during the application execution. In practice, the prediction of application characteristics may be approximative or completely infeasible. For instance, the amount of computations and of communications required to solve a given problem in parallel may strongly depend on some input data that are hard to analyze (this is for instance the case when solving linear systems using full pivoting).

We plan to consider applications whose characteristics change dynamically and are subject to uncertainties. In order to benefit nonetheless from the power of static approaches, we plan to model application uncertainties and variations through probabilistic models, and to design for these applications scheduling strategies that are either static, or partially static and partially dynamic.

3.2. Platform-aware scheduling strategies

In this theme, we study and design scheduling strategies, focusing either on energy consumption or on memory behavior. In other words, when designing and evaluating these strategies, we do not limit our view to the most classical platform characteristics, that is, the computing speed of cores and accelerators, and the bandwidth of communication links.

In most existing studies, a single optimization objective is considered, and the target is some sort of absolute performance. For instance, most optimization problems aim at the minimization of the overall execution time of the application considered. Such an approach can lead to a very significant waste of resources, because it does not take into account any notion of efficiency nor of yield. For instance, it may not be meaningful to use twice as many resources just to decrease by 10% the execution time. In all our work, we plan to look only for algorithmic solutions that make a "clever" usage of resources. However, looking for the solution that optimizes a metric such as the efficiency, the energy consumption, or the memory-peak minimization, is doomed for the type of applications we consider. Indeed, in most cases, any optimal solution for such a metric is a sequential solution, and sequential solutions have prohibitive execution times. Therefore, it becomes mandatory to consider multi-criteria approaches where one looks for trade-offs between some user-oriented metrics that are typically related to notions of Quality of Service—execution time, response time, stretch, throughput, latency, reliability, etc.—and some system-oriented metrics that guarantee that resources are not wasted. In general, we will not look for the Pareto curve, that is, the set of all dominating solutions for the considered metrics. Instead, we will rather look for solutions that minimize some given objective while satisfying some bounds, or "budgets", on all the other objectives.

3.2.1. Energy-aware algorithms

Energy-aware scheduling has proven an important issue in the past decade, both for economical and environmental reasons. Energy issues are obvious for battery-powered systems. They are now also important for traditional computer systems. Indeed, the design specifications of any new computing platform now always include an upper bound on energy consumption. Furthermore, the energy bill of a supercomputer may represent a significant share of its cost over its lifespan.

Technically, a processor running at speed s dissipates s^α watts per unit of time with $2 \leq \alpha \leq 3$ [70], [71], [76]; hence, it consumes $s^\alpha \times d$ joules when operated during d units of time. Therefore, energy consumption can be reduced by using speed scaling techniques. However it was shown in [92] that reducing the speed of a processor increases the rate of transient faults in the system. The probability of faults increases exponentially, and this probability cannot be neglected in large-scale computing [88]. In order to make up for the loss in *reliability* due to the energy efficiency, different models have been proposed for fault tolerance: (i) *re-execution* consists in re-executing a task that does not meet the reliability constraint [92]; (ii) *replication* consists in executing the same task on several processors simultaneously, in order to meet the reliability constraints [69]; and (iii) *checkpointing* consists in "saving" the work done at some certain instants, hence reducing the amount of work lost when a failure occurs [87].

Energy issues must be taken into account at all levels, including the algorithm-design level. We plan to both evaluate the energy consumption of existing algorithms and to design new algorithms that minimize energy consumption using tools such as resource selection, dynamic frequency and voltage scaling, or powering-down of hardware components.

3.2.2. Memory-aware algorithms

For many years, the bandwidth between memories and processors has increased more slowly than the computing power of processors, and the latency of memory accesses has been improved at an even slower pace. Therefore, in the time needed for a processor to perform a floating point operation, the amount of data transferred between the memory and the processor has been decreasing with each passing year. The risk is for an application to reach a point where the time needed to solve a problem is no longer dictated by the processor computing power but by the memory characteristics, comparable to the *memory wall* that limits CPU performance. In such a case, processors would be greatly under-utilized, and a large part of the computing power of the platform would be wasted. Moreover, with the advent of multicore processors, the amount of memory per core has started to stagnate, if not to decrease. This is especially harmful to memory intensive applications. The problems related to the sizes and the bandwidths of memories are further exacerbated on modern computing platforms because of their deep and highly heterogeneous hierarchies. Such a hierarchy can extend from core private caches to shared memory within a CPU, to disk storage and even tape-based storage systems, like in the Blue Waters supercomputer [63]. It may also be the case that heterogeneous cores are used (such as hybrid CPU and GPU computing), and that each of them has a limited memory.

Because of these trends, it is becoming more and more important to precisely take memory constraints into account when designing algorithms. One must not only take care of the amount of memory required to run an algorithm, but also of the way this memory is accessed. Indeed, in some cases, rather than to minimize the amount of memory required to solve the given problem, one will have to maximize data reuse and, especially, to minimize the amount of data transferred between the different levels of the memory hierarchy (minimization of the volume of memory inputs-outputs). This is, for instance, the case when a problem cannot be solved by just using the in-core memory and that any solution must be out-of-core, that is, must use disks as storage for temporary data.

It is worth noting that the cost of moving data has lead to the development of so called "communication-avoiding algorithms" [84]. Our approach is orthogonal to these efforts: in communication-avoiding algorithms, the application is modified, in particular some redundant work is done, in order to get rid of some communication operations, whereas in our approach, we do not modify the application, which is provided as a task graph, but we minimize the needed memory peak only by carefully scheduling tasks.

3.3. High-performance computing and linear algebra

Our work on high-performance computing and linear algebra is organized along three research directions. The first direction is devoted to direct solvers of sparse linear systems. The second direction is devoted to combinatorial scientific computing, that is, the design of combinatorial algorithms and tools that solve problems encountered in some of the other research themes, like the problems faced in the preprocessing phases of sparse direct solvers. The last direction deals with the adaptation of classical dense linear algebra kernels to the architecture of future computing platforms.

3.3.1. Direct solvers for sparse linear systems

The solution of sparse systems of linear equations (symmetric or unsymmetric, often with an irregular structure, from a few hundred thousand to a few hundred million equations) is at the heart of many scientific applications arising in domains such as geophysics, structural mechanics, chemistry, electromagnetism, numerical optimization, or computational fluid dynamics, to cite a few. The importance and diversity of applications are a main motivation to pursue research on sparse linear solvers. Because of this wide range of applications, any significant progress on solvers will have a significant impact in the world of simulation. Research on sparse direct solvers in general is very active for the following main reasons:

- many applications fields require large-scale simulations that are still too big or too complicated with respect to today's solution methods;
- the current evolution of architectures with massive, hierarchical, multicore parallelism imposes to overhaul all existing solutions, which represents a major challenge for algorithm and software development;
- the evolution of numerical needs and types of simulations increase the importance, frequency, and size of certain classes of matrices, which may benefit from a specialized processing (rather than resort to a generic one).

Our research in the field is strongly related to the software package MUMPS (see Section 5.1). MUMPS is both an experimental platform for academics in the field of sparse linear algebra, and a software package that is widely used in both academia and industry. The software package MUMPS enables us to (i) confront our research to the real world, (ii) develop contacts and collaborations, and (iii) receive continuous feedback from real-life applications, which is extremely critical to validate our research work. The feedback from a large user community also enables us to direct our long-term objectives towards meaningful directions.

In this context, we aim at designing parallel sparse direct methods that will scale to large modern platforms, and that are able to answer new challenges arising from applications, both efficiently—from a resource consumption point of view—and accurately—from a numerical point of view. For that, and even with increasing parallelism, we do not want to sacrifice in any manner numerical stability, based on threshold partial pivoting, one of the main originalities of our approach (our "trademark") in the context of direct solvers for distributed-memory computers; although this makes the parallelization more complicated, applying the same pivoting strategy as in the serial case ensures numerical robustness of our approach, which we generally measure in terms of sparse backward error. In order to solve the hard problems resulting from the always-increasing demands in simulations, special attention must also necessarily be paid to memory usage (and not only execution time). This requires specific algorithmic choices and scheduling techniques. From a complementary point of view, it is also necessary to be aware of the functionality requirements from the applications and from the users, so that robust solutions can be proposed for a wide range of applications.

Among direct methods, we rely on the multifrontal method [80], [81], [86]. This method usually exhibits a good data locality and hence is efficient in cache-based systems. The task graph associated with the multifrontal method is in the form of a tree whose characteristics should be exploited in a parallel implementation.

Our work is organized along two main research directions. In the first one we aim at efficiently addressing new architectures that include massive, hierarchical parallelism. In the second one, we aim at reducing the running time complexity and the memory requirements of direct solvers, while controlling accuracy.

3.3.2. Combinatorial scientific computing

Combinatorial scientific computing (CSC) is a recently coined term (circa 2002) for interdisciplinary research at the intersection of discrete mathematics, computer science, and scientific computing. In particular, it refers to the development, application, and analysis of combinatorial algorithms to enable scientific computing applications. CSC's deepest roots are in the realm of direct methods for solving sparse linear systems of equations where graph theoretical models have been central to the exploitation of sparsity, since the 1960s. The general approach is to identify performance issues in a scientific computing problem, such as memory use, parallel speed up, and/or the rate of convergence of a method, and to develop combinatorial algorithms and models to tackle those issues.

Our target scientific computing applications are (i) the preprocessing phases of direct methods (in particular MUMPS), iterative methods, and hybrid methods for solving linear systems of equations; and (ii) the mapping of tasks (mostly the sub-tasks of the mentioned solvers) onto modern computing platforms. We focus on the development and use of graph and hypergraph models, and related tools such as hypergraph partitioning algorithms, to solve problems of load balancing and task mapping. We also focus on bipartite graph matching and vertex ordering methods for reducing the memory overhead and computational requirements of solvers. Although we direct our attention on these models and algorithms through the lens of linear system solvers, our solutions are general enough to be applied to some other resource optimization problems.

3.3.3. Dense linear algebra on post-petascale multicore platforms

The quest for efficient, yet portable, implementations of dense linear algebra kernels (QR, LU, Cholesky) has never stopped, fueled in part by each new technological evolution. First, the LAPACK library [74] relied on BLAS level 3 kernels (Basic Linear Algebra Subroutines) that enable to fully harness the computing power of a single CPU. Then the SCALAPACK library [73] built upon LAPACK to provide a coarse-grain parallel version, where processors operate on large block-column panels. Inter-processor communications occur through highly tuned MPI send and receive primitives. The advent of multi-core processors has led to a major modification in these algorithms [75], [89], [85]. Each processor runs several threads in parallel to keep all cores within that processor busy. Tiled versions of the algorithms have thus been designed: dividing large block-column panels into several tiles allows for a decrease in the granularity down to a level where many smaller-size tasks are spawned. In the current panel, the diagonal tile is used to eliminate all the lower tiles in the panel. Because the factorization of the whole panel is now broken into the elimination of several tiles, the update operations can also be partitioned at the tile level, which generates many tasks to feed all cores.

The number of cores per processor will keep increasing in the following years. It is projected that high-end processors will include at least a few hundreds of cores. This evolution will require to design new versions of libraries. Indeed, existing libraries rely on a static distribution of the work: before the beginning of the execution of a kernel, the location and time of the execution of all of its component is decided. In theory, static solutions enable to precisely optimize executions, by taking parameters like data locality into account. At run time, these solutions proceed at the pace of the slowest of the cores, and they thus require a perfect load-balancing. With a few hundreds, if not a thousand, cores per processor, some tiny differences between the computing times on the different cores (“jitter”) are unavoidable and irremediably condemn purely static solutions. Moreover, the increase in the number of cores per processor once again mandates to increase the number of tasks that can be executed in parallel.

We study solutions that are part-static part-dynamic, because such solutions have been shown to outperform purely dynamic ones [77]. On the one hand, the distribution of work among the different nodes will still be statically defined. On the other hand, the mapping and the scheduling of tasks inside a processor will be dynamically defined. The main difficulty when building such a solution will be to design lightweight dynamic schedulers that are able to guarantee both an excellent load-balancing and a very efficient use of data locality.

RUNTIME Project-Team

3. Research Program

3.1. Runtime Systems Evolution

parallel,distributed,cluster,environment,library,communication,multithreading,multicore

This research project takes place within the context of high-performance computing. It seeks to contribute to the design and implementation of parallel runtime systems that shall serve as a basis for the implementation of high-level parallel middleware. Today, the implementation of such software (programming environments, numerical libraries, parallel language compilers, parallel virtual machines, etc.) has become so complex that the use of portable, low-level runtime systems is unavoidable.

Our research project centers on three main directions:

Mastering large, hierarchical multiprocessor machines With the beginning of the new century, computer makers have initiated a long term move of integrating more and more processing units, as an answer to the frequency wall hit by the technology. This integration cannot be made in a basic, planar scheme beyond a couple of processing units for scalability reasons. Instead, vendors have to resort to organize those processing units following some hierarchical structure scheme. A level in the hierarchy is then materialized by small groups of units sharing some common local cache or memory bank. Memory accesses outside the locality of the group are still possible thanks to bus-level consistency mechanisms but are significantly more expensive than local accesses, which, by definition, characterizes NUMA architectures.

Thus, the task scheduler must feed an increasing number of processing units with work to execute and data to process while keeping the rate of penalized memory accesses as low as possible. False sharing, ping-pong effects, data vs task locality mismatches, and even task vs task locality mismatches between tightly synchronizing activities are examples of the numerous sources of overhead that may arise if threads and data are not distributed properly by the scheduler. To avoid these pitfalls, the scheduler therefore needs accurate information both about the computing platform layout it is running on and about the structure and activities relationships of the application it is scheduling.

As quoted by Gao *et al.* [43], we believe it is important to expose domain-specific knowledge semantics to the various software components in order to organize computation according to the application and architecture. Indeed, the whole software stack, from the application to the scheduler, should be involved in the parallelizing, scheduling and locality adaptation decisions by providing useful information to the other components. Unfortunately, most operating systems only provide a poor scheduling API that does not allow applications to transmit valuable *hints* to the system.

This is why we investigate new approaches in the design of thread schedulers, focusing on high-level abstractions to both model hierarchical architectures and describe the structure of applications' parallelism. In particular, we have introduced the *bubble* scheduling concept [7] that helps to structure relations between threads in a way that can be efficiently exploited by the underlying thread scheduler. *Bubbles* express the inherent parallel structure of multithreaded applications: they are abstractions for grouping threads which “work together” in a recursive way. We are exploring how to dynamically schedule these irregular nested sets of threads on hierarchical machines [3], the key challenge being to schedule related threads as closely as possible in order to benefit from cache effects and avoid NUMA penalties. We are also exploring how to improve the transfer of scheduling hints from the programming environment to the runtime system, to achieve better computation efficiency.

This is also the reason why we explore new languages and compiler optimizations to better use domain specific information. We propose a new domain specific language, QIRAL, to generate parallel codes from high level formulations for Lattice QCD problems. QIRAL describes the formulation of the algorithms, of the matrices and preconditions used in this domain and generalizes languages such as SPIRAL used in auto-tuning library generator for signal processing applications. Lattice QCD applications require huge amount of processing power, on multinode, multi-core with GPUs. Simulation codes require to find new algorithms and efficient parallelization. So far, the difficulties for orchestrating parallelism efficiently hinder algorithmic exploration. The objective of QIRAL is to decouple algorithm exploration with parallelism description. Compiling QIRAL uses rewriting techniques for algorithm exploration, parallelization techniques for parallel code generation and potentially, runtime support to orchestrate this parallelism. Results of this work have been published in [9]. A similar approach, this time targeting methods to solve matrix equations, has been proposed [17]. Hydra focuses on systems of equations involving regular shaped matrices (such as upper triangular for instance) and finds automatically a parallel method to solve this system. The approach, using to a divide and conquer technique, works for several equations such as LU decomposition, Sylvester equation and has been shown to be comparable or outperforming Intel MKL library on multicores. Hydra relies on STARPU.

For parallel programs running on multicores, thread affinity and data locality is essential for performance. We investigated in [23] how thread pinning strategies could impact performance and performance stability and compared the efficiency of several profile-guided strategies with compile-time strategies. Following this effort, in MAQAO, we developped a language to ease the instrumentation of parallel codes, in particular for capturing memory traces [16]. Through the combined analysis of the code behavior, at compile time and at runtime, MAQAO can then help users to better pinpoint and quantify performance issues in OpenMP codes, find load imbalance between threads, size of working sets, false sharing situations... The MAQAO instrumentation language has been used successfully in other tools, such as TAU. Besides, we proposed in [15] to combine static and dynamic dependence analysis for the detection of vectorization opportunities. MAQAO then estimates the potential gain that could be reached through vectorization and identifies the required code transformations, either by changing loop control or data layout.

Aside from greedily invading all these new cores, demanding HPC applications now throw excited glances at the appealing computing power left unharvested inside the graphical processing units (GPUs). A strong demand is arising from the application programmers to be given means to access this power without bearing an unaffordable burden on the portability side. Efforts have already been made by the community in this respect but the tools provided still are rather close to the hardware, if not to the metal. Hence, we decided to launch some investigations on addressing this issue. In particular, we have designed a programming environment named STARPU that enables the programmer to offload tasks onto such heterogeneous processing units and gives that programmer tools to fit tasks to processing units capability, tools to efficiently manage data moves to and from the offloading hardware and handles the scheduling of such tasks all in an abstracted, portable manner. The challenge here is to take into account the intricacies of all computation unit: not only the computation power is heterogeneous among the machine, but data transfers themselves have various behavior depending on the machine architecture and GPUs capabilities, and thus have to be taken into account to get the best performance from the underlying machine. As a consequence, STARPU not only pays attention to fully exploit each of the different computational resources at the same time by properly mapping tasks in a dynamic manner according to their computation power and task behavior by the means of scheduling policies, but it also provides a distributed shared-memory library that makes it possible to manipulate data across heterogeneous multicore architectures in a high-level fashion while being optimized according to the machine possibilities. In addition to this, the scheduling policy of STARPU has been modularized; this makes it easy to experiment with state of the art theoretical scheduling strategies. Last but not least, STARPU works over clusters, by extending the shared-memory view over the MPI communication library. This allows, with the same sequential-looking application source code, to tackle all architectures from small multicore systems to clusters of heterogeneous systems.

We extended OpenCL capabilities by proposing to use, transparently, STARPU as an OpenCL device [35]. A functional approach to STARPU has been proposed besides in [18].

Optimizing communications over high performance clusters and grids Using a large panel of mechanisms such as user-mode communications, zero-copy transactions and communication operation offload, the critical path in sending and receiving a packet over high speed networks has been drastically reduced over the years. Recent implementations of the MPI standard, which have been carefully designed to directly map *basic* point-to-point requests onto the underlying low-level interfaces, almost reach the same level of performance for very basic point-to-point messaging requests. However more complex requests such as non-contiguous messages are left mostly unattended, and even more so are the irregular and multiflow communication schemes. The intent of the work on our NEWMADELEINE communication engine, for instance, is to address this situation thoroughly. The NEWMADELEINE optimization layer delivers much better performance on *complex* communication schemes with negligible overhead on basic single packet point-to-point requests. Through Mad-MPI, our proof-of-concept implementation of a subset of the MPI API, we intend to show that MPI applications can also benefit from the NEWMADELEINE communication engine.

The increasing number of cores in cluster nodes also raises the importance of intra-node communication. Our KNEM software module aims at offering optimized communication strategies for this special case and let the above MPI implementations benefit from dedicated models depending on process placement and hardware characteristics.

Moreover, the convergence between specialized high-speed networks and traditional ETHERNET networks leads to the need to adapt former software and hardware innovations to new message-passing stacks. Our work on the OPEN-MX software is carried out in this context.

Regarding larger scale configurations (clusters of clusters, grids), we intend to propose new models, principles and mechanisms that should allow to combine communication handling, threads scheduling and I/O event monitoring on such architectures, both in a portable and efficient way. We particularly intend to study the introduction of new runtime system functionalities to ease the development of code-coupling distributed applications, while minimizing their unavoidable negative impact on the application performance.

Integrating Communications and Multithreading Asynchronism is becoming ubiquitous in modern communication runtimes. Complex optimizations based on online analysis of the communication schemes and on the de-coupling of the request submission vs processing. Flow multiplexing or transparent heterogeneous networking also imply an active role of the runtime system request submit and process. And communication overlap as well as reactiveness are critical. Since network request cost is in the order of magnitude of several thousands CPU cycles at least, independent computations should not get blocked by an ongoing network transaction. This is even more true with the increasingly dense SMP, multicore, SMT architectures where many computing units share a few NICs. Since portability is one of the most important requirements for communication runtime systems, the usual approach to implement asynchronous processing is to use threads (such as Posix threads). Popular communication runtimes indeed are starting to make use of threads internally and also allow applications to also be multithreaded. Low level communication libraries also make use of multithreading. Such an introduction of threads inside communication subsystems is not going without troubles however. The fact that multithreading is still usually optional with these runtimes is symptomatic of the difficulty to get the benefits of multithreading in the context of networking without suffering from the potential drawbacks. We advocate the importance of the cooperation between the asynchronous event management code and the thread scheduling code in order to avoid such disadvantages. We intend to propose a framework for symbiotically combining both approaches inside a new generic I/O event manager.

Moreover, the design of distributed parallel code, integrating both MPI and OpenMP, is complex and error-prine. Deadlock situations may arise and are difficult to detect. We proposed an original approach, based on static (compile-time) analysis and runtime verification in order to detect deadlock situation but also to pinpoint the cause of such deadlock [27]. This work first focuses on MPI communication alone, the extension to hybrid MPI/OpenMP codes is in progress.

ASCOLA Project-Team

3. Research Program

3.1. Overview

Since we mainly work on new software structuring concepts and programming language design, we first briefly introduce some basic notions and problems of software components (understood in a broad sense, i.e., including modules, objects, architecture description languages and services), aspects, and domain-specific languages. We conclude by presenting the main issues related to distribution and concurrency that are relevant to our work.

3.2. Software Composition

Modules and services. The idea that building *software components*, i.e., composable prefabricated and parameterized software parts, was key to create an effective software industry was realized very early [86]. At that time, the scope of a component was limited to a single procedure. In the seventies, the growing complexity of software made it necessary to consider a new level of structuring and programming and led to the notions of information hiding, *modules*, and module interconnection languages [93], [71]. Information hiding promotes a black-box model of program development whereby a module implementation, basically a collection of procedures, is strongly encapsulated behind an interface. This makes it possible to guarantee logical invariant *properties* of the data managed by the procedures and, more generally, makes *modular reasoning* possible.

In the context of today's Internet-based information society, components and modules have given rise to *software services* whose compositions are governed by explicit *orchestration or choreography* specifications that support notions of global properties of a service-oriented architecture. These horizontal compositions have, however, to be frequently adapted dynamically. Dynamic adaptations, in particular in the context of software evolution processes, often conflict with a black-box composition model either because of the need for invasive modifications, for instance, in order to optimize resource utilization or modifications to the vertical compositions implementing the high-level services.

Object-Oriented Programming.*Classes* and *objects* provide another kind of software component, which makes it necessary to distinguish between *component types* (classes) and *component instances* (objects). Indeed, unlike modules, objects can be created dynamically. Although it is also possible to talk about classes in terms of interfaces and implementations, the encapsulation provided by classes is not as strong as the one provided by modules. This is because, through the use of inheritance, object-oriented languages put the emphasis on *incremental programming* to the detriment of modular programming. This introduces a white-box model of software development and more flexibility is traded for safety as demonstrated by the *fragile base class* issue [89].

Architecture Description Languages. The advent of distributed applications made it necessary to consider more sophisticated connections between the various building blocks of a system. The *software architecture* [97] of a software system describes the system as a composition of *components* and *connectors*, where the connectors capture the *interaction protocols* between the components [62]. It also describes the rationale behind such a given architecture, linking the properties required from the system to its implementation. *Architecture Description Languages* (ADLs) are languages that support architecture-based development [87]. A number of these languages make it possible to generate executable systems from architectural descriptions, provided implementations for the primitive components are available. However, guaranteeing that the implementation conforms to the architecture is an issue.

Protocols. Today, protocols constitute a frequently used means to precisely define, implement, and analyze contracts between two or more hardware or software entities. They have been used to define interactions between communication layers, security properties of distributed communications, interactions between objects and components, and business processes.

Object interactions [91], component interactions [103], [95] and service orchestrations [72] are most frequently expressed in terms of *regular interaction protocols* that enable basic properties, such as compatibility, substitutability, and deadlocks between components to be defined in terms of basic operations and closure properties of finite-state automata. Furthermore, such properties may be analyzed automatically using, e.g., model checking techniques [69], [78].

However, the limited expressive power of regular languages has led to a number of approaches using more expressive *non-regular* interaction protocols that often provide distribution-specific abstractions, e.g., session types [80], or context-free or turing-complete expressiveness [96], [67]. While these protocol types allow conformance between components to be defined (e.g., using unbounded counters), property verification can only be performed manually or semi-automatically.

3.3. Programming languages for advanced modularization

The main driving force for the structuring means, such as components and modules, is the quest for clean *separation of concerns* [73] on the architectural and programming levels. It has, however, early been noted that concern separation in the presence of crosscutting functionalities requires specific language and implementation level support. Techniques of so-called *computational reflection*, for instance, Smith's 3-Lisp or Kiczales's CLOS meta-object protocol [98], [83] as well as metaprogramming techniques have been developed to cope with this problem but proven unwieldy to use and not amenable to formalization and property analysis due to their generality. Methods and techniques from two fields have been particularly useful in addressing such advanced modularization problems: Aspect-Oriented Software Development as the field concerned with the systematic handling of modularization issues and domain-specific languages that provide declarative and efficient means for the definition of crosscutting functionalities.

Aspect-Oriented Software Development [82], [60] has emerged over the previous decade as the domain of systematic exploration of crosscutting concerns and corresponding support throughout the software development process. The corresponding research efforts have resulted, in particular, in the recognition of *crosscutting* as a fundamental problem of virtually any large-scale application, and the definition and implementation of a large number of aspect-oriented models and languages.

However, most current aspect-oriented models, notably AspectJ [81], rely on pointcuts and advice defined in terms of individual execution events. These models are subject to serious limitations concerning the modularization of crosscutting functionalities in distributed applications, the integration of aspects with other modularization mechanisms such as components, and the provision of correctness guarantees of the resulting AO applications. They do, in particular, only permit the manipulation of distributed applications on a per-host basis, that is, without direct expression of coordination properties relating different distributed entities [99]. Similarly, current approaches for the integration of aspects and (distributed) components do not directly express interaction properties between sets of components but rather seemingly unrelated modifications to individual components [70]. Finally, current formalizations of such aspect models are formulated in terms of low-level semantic abstractions (see, e.g., Wand's et al semantics for AspectJ [102]) and provide only limited support for the analysis of fundamental aspect properties.

Recently, first approaches have been put forward to tackle these problems, in particular, in the context of so-called *stateful* or *history-based aspect languages* [74], [75], which provide pointcut and advice languages that directly express rich relationships between execution events. Such languages have been proposed to directly express coordination and synchronization issues of distributed and concurrent applications [92], [65], [77], provide more concise formal semantics for aspects and enable analysis of their properties [63], [76], [74], [61]. Furthermore, first approaches for the definition of *aspects over protocols* have been proposed, as well as over regular structures [74] and non-regular ones [101], [90], which are helpful for the modular definition and verification of protocols over crosscutting functionalities.

Due to the novelty of these approaches, they represent, however, only first results and many important questions concerning these fundamental issues remain open.

Domain-specific languages (DSLs) represent domain knowledge in terms of suitable basic language constructs and their compositions at the language level. By trading generality for abstraction, they enable complex relationships among domain concepts to be expressed concisely and their properties to be expressed and formally analyzed. DSLs have been applied to a large number of domains; they have been particularly popular in the domain of software generation and maintenance [88], [104].

Many modularization techniques and tasks can be naturally expressed by DSLs that are either specialized with respect to the type of modularization constructs, such as a specific brand of software component, or to the compositions that are admissible in the context of an application domain that is targeted by a modular implementation. Moreover, software development and evolution processes can frequently be expressed by transformations between applications implemented using different DSLs that represent an implementation at different abstraction levels or different parts of one application.

Functionalities that crosscut a component-based application, however, complicate such a DSL-based transformational software development process. Since such functionalities belong to another domain than that captured by the components, different DSLs should be composed. Such compositions (including their syntactic expression, semantics and property analysis) have only very partially been explored until now. Furthermore, restricted composition languages and many aspect languages that only match execution events of a specific domain (e.g., specific file accesses in the case of security functionality) and trigger only domain-specific actions clearly are quite similar to DSLs but remain to be explored.

3.4. Distribution and Concurrency

While ASCOLA does not investigate distribution and concurrency as research domains per se (but rather from a software engineering and modularization viewpoint), there are several specific problems and corresponding approaches in these domains that are directly related to its core interests that include the structuring and modularization of large-scale distributed infrastructures and applications. These problems include crosscutting functionalities of distributed and concurrent systems, support for the evolution of distributed software systems, and correctness guarantees for the resulting software systems.

Underlying our interest in these domains is the well-known observation that large-scale distributed applications are subject to *numerous crosscutting functionalities* (such as the transactional behavior in enterprise information systems, the implementation of security policies, and fault recovery strategies). These functionalities are typically partially encapsulated in distributed infrastructures and partially handled in an ad hoc manner by using infrastructure services at the application level. Support for a more principled approach to the development and evolution of distributed software systems in the presence of crosscutting functionalities has been investigated in the field of *open adaptable middleware* [66], [85]. Open middleware design exploits the concept of reflection to provide the desired level of configurability and openness. However, these approaches are subject to several fundamental problems. One important problem is their insufficient, framework-based support that only allows partial modularization of crosscutting functionalities.

There has been some *criticism* on the use of *AspectJ-like aspect models* (which middleware aspect models like that of JBoss AOP are an instance of) for the modularization of distribution and concurrency related concerns, in particular, for transaction concerns [84] and the modularization of the distribution concern itself [99]. Both criticisms are essentially grounded in AspectJ's inability to explicitly represent sophisticated relationships between execution events in a distributed system: such aspects therefore cannot capture the semantic relationships that are essential for the corresponding concerns. History-based aspects, as those proposed by the ASCOLA project-team provide a starting point that is not subject to this problem.

From a point of view of language design and implementation, aspect languages, as well as domain specific languages for distributed and concurrent environments share many characteristics with existing distributed languages: for instance, event monitoring is fundamental for pointcut matching, different synchronization strategies and strategies for code mobility [79] may be used in actions triggered by pointcuts. However, these relationships have only been explored to a small degree. Similarly, the formal semantics and formal properties of aspect languages have not been studied yet for the distributed case and only rudimentarily for the concurrent one [63], [77].

3.5. Security

Security properties and policies over complex service-oriented and standalone applications become ever more important in the context of asynchronous and decentralized communicating systems. Furthermore, they constitute prime examples of crosscutting functionalities that can only be modularized in highly insufficient ways with existing programming language and service models. Security properties and related properties, such as accountability properties, are therefore very frequently awkward to express and difficult to analyze and enforce (provided they can be made explicit in the first place).

Two main issues in this space are particularly problematic from a compositional point of view. First, information flow properties of programming languages, such as flow properties of Javascript [64], and service-based systems [68] are typically specially-tailored to specific properties, as well as difficult to express and analyze. Second, the enforcement of security properties and security policies, especially accountability-related properties [94], [100], is only supported using ad hoc means with rudimentary support for property verification.

The ASCOLA team has recently started to work on providing formal methods, language support and implementation techniques for the modular definition and implementation of information flow properties as well as policy enforcement in service-oriented systems as well as, mostly object-oriented, programming languages.

3.6. Capacity Planning for Large Scale Distributed System

Since the last decade, cloud computing has emerged as both a new economic model for software (provision) and as flexible tools for the management of computing capacity. Nowadays, the major cloud features have become part of the mainstream (virtualization, storage and software image management) and the big market players offer effective cloud-based solutions for resource pooling. It is now possible to deploy virtual infrastructures that involve virtual machines (VMs), middleware, applications, and networks in such a simple manner that a new problem has emerged over the last two years: VM sprawl (virtual machine proliferation) that consumes valuable computing, memory, storage and energy resources, thus menacing serious resource shortages. Scientific approaches that address VM sprawl are both based on classical administration techniques like the lifecycle management of a large number of VMs as well as the arbitration and the careful management of all resources consumed and provided by the hosting infrastructure (energy, power, computing, memory, network etc.).

The ASCOLA team investigates fundamental techniques for cloud computing and capacity planning, from infrastructures to the application level. Capacity planning is the process of planning for, analyzing, sizing, managing and optimizing capacity to satisfy demand in a timely manner and at a reasonable cost. Applied to distributed systems like clouds, a capacity planning solution must mainly provide the minimal set of resources necessary for the proper execution of the applications (i.e., to ensure SLA). The main challenges in this context are: scalability, fault tolerance and reactivity of the solution in a large-scale distributed system, the analysis and optimization of resources to minimize the cost (mainly costs related to the energy consumption of datacenters), as well as the profiling and adaptation of applications to ensure useful levels of quality of service (throughput, response time, availability etc.).

Our solutions are mainly based on virtualized infrastructures that we apply from the IaaS to the SaaS levels. We are mainly concerned by the management and the execution of the applications by harnessing virtualization capabilities, the investigation of alternative solutions that aim at optimizing the trade-off between performance and energy costs of both applications and cloud resources, as well as arbitration policies in the cloud in the presence of energy-constrained resources.

FOCUS Project-Team

3. Research Program

3.1. Models

The objective of Focus is to develop concepts, techniques, and possibly also tools, that may contribute to the analysis and synthesis of CBUS. Fundamental to these activities is *modeling*. Therefore designing, developing and studying computational models appropriate for CBUS is a central activity of the project. The models are used to formalize and verify important computational properties of the systems, as well as to propose new linguistic constructs.

The models we study are in the process calculi (e.g., the π-calculus) and λ-calculus tradition. Such models, with their emphasis on algebra, well address compositionality—a central property in our approach to problems. Accordingly, the techniques we employ are mainly operational techniques based on notions of behavioral equivalence, and techniques based on algebra, mathematical logics, and type theory.

The sections below provide some more details on why process calculi, λ-calculi, and related techniques, should be useful for CBUS.

OASIS Project-Team

3. Research Program

3.1. Programming with distributed objects and components

The paradigm of object-oriented programming, although not very recent, is clearly still not properly defined and implemented; for example notions like inheritance, sub-typing or overloading have as many definitions as there are different object languages. The introduction of concurrency and distribution into objects also increases the complexity. It appeared that standard Java constituents such as RMI (Remote Method Invocation) do not help building, in a transparent way, sequential, multi-threaded, or distributed applications. Indeed allowing, as RMI does, the execution of the same application to proceed on a shared-memory multiprocessors architecture as well as on a network of computing units (intranet, Internet), or on any hierarchical combination of both, is not sufficient for providing a convenient and reliable programming environment.

The question is thus: how to ease the construction (i.e. programming), deployment and evolution of distributed applications?

One of the answers we suggest relies on the concept of active object, that acts as a single entity, abstraction of a thread, a set of objects and a location. Active objects communicate by asynchronous method calls thanks to the use of futures. ProActive is a Java library that implements this notion of active objects. ProActive can also be seen as a middleware supporting deployment, runtime support, and efficient communication for large scale distributed applications.

Another answer we provide relies on component-oriented programming. In particular, we have defined parallel and hierarchical distributed components starting from the Fractal component model developed by Inria and France-Telecom [41]. We have been involved in the design of the Grid Component Model (GCM) [4], which is one of the major results produced by the CoreGrid European Network of Excellence. The GCM has been standardized at ETSI ([45] for the last published standard), and most of our research on component models are related to it. On the practical side, ProActive/GCM is the implementation of the GCM above the ProActive programming library.

We have developed over time skills in both theoretical and applicative side fields, such as distribution, fault-tolerance, verification, etc., to provide a better programming and runtime environment for object oriented and component oriented applications.

3.2. Formal models for distributed objects

A few years ago, we designed the ASP calculus [6] for modelling distributed objects. It remains to this date one of our major scientific foundations. ASP is a calculus for distributed objects interacting using asynchronous method calls with generalized futures. Those futures naturally come with a transparent and automatic synchronisation called wait-by-necessity. In large-scale systems, our approach provides both a good structure and a strong decoupling between threads, and thus scalability. Our work on ASP provides very generic results on expressiveness and determinism, and the potential of this approach has been further demonstrated by its capacity to cope with advanced issues, such as mobility, group communications, and components [6].

ASP provides confluence and determinism properties for distributed objects. Such results should allow one to program parallel and distributed applications that behave in a deterministic manner, even if they are distributed over local or wide area networks.

The ASP calculus is a model for the ProActive library. An extension of ASP has been built to model distributed asynchronous components. A functional fragment of ASP has been modelled in the Isabelle theorem prover [8].

3.3. Verification, static analysis, and model-checking

Even with the help of high-level libraries, distributed systems are more difficult to program than classical applications. The complexity of interactions and synchronisations between remote parts of a system increases the difficulty of analysing their behaviours. Consequently, safety, security, or liveness properties are particularly difficult to ensure for these applications. Formal verification of software systems has been active for a long time, but its impact on the development methodology and tools has been slower than in the domain of hardware and circuits. This is true both at a theoretical and at a practical level; our contributions include:

- the definition of adequate models representing programs,
- the mastering of state complexity through abstraction techniques, new algorithmic approaches, or research on advanced parallel or distributed verification methods,
- the design of software tools that hide to the final user the complexity of the underlying theory.

We concentrate on the area of distributed component systems, where we get better descriptions of the structure of the system, making the analysis more tractable, but we also find out new interesting problems. For instance, we contributed to a better analysis of the interplay between the functional definition of a component and its possible runtime transformations, expressed by the various management controllers of the component system.

Our approach is bi-directional: from models to program, or back. We use techniques of static analysis and abstract interpretation to extract models from the code of distributed applications, or from dedicated specification formalisms [3]. On the other hand, we generate “safe by construction” code skeletons, from high level specifications; this guarantees the behavioural properties of the components. We then use generic tools from the verification community to check properties of these models. We concentrate on behavioural properties, expressed in terms of temporal logics (safety, liveness), of adequacy of an implementation to its specification and of correct composition of software components.

PHOENIX Project-Team

3. Research Program

3.1. Design-Driven Software Development

Raising the level of abstraction beyond programming is a very active research topic involving a range of areas, including software engineering, programming languages and formal verification. The challenge is to allow design dimensions of a software system, both functional and non-functional, to be expressed in a high-level way, instead of being encoded with a programming language. Such design dimensions can then be leveraged to verify conformance properties and to generate programming support.

Our research on this topic is to take up this challenge with an approach inspired by programming languages, introducing a full-fledged language for designing software systems and processing design descriptions both for verification and code generation purposes. Our approach is also DSL-inspired in that it defines a conceptual framework to guide software development. Lastly, to make our approach practical to software developers, we introduce a methodology and a suite of tools covering the development life-cycle.

To raise the level of abstraction beyond programming, the key approaches are model-driven engineering and architecture description languages. A number of *architecture description languages* have been proposed; they are either (1) coupled with a programming language (*e.g.,* [32]), providing some level of abstraction above programming, or (2) integrated into a programming language (*e.g.,* [26], [33]), mixing levels of abstraction. Furthermore, these approaches poorly leverage architecture descriptions to support programming, they are crudely integrated into existing development environments, or they are solely used for verification purposes. *Model-driven software development* is another actively researched area. This approach often lacks code generation and verification support. Finally, most (if not all) approaches related to our research goal are *general purpose*; their universal nature provides little, if any, guidance to design a software system. This situation is a major impediment to both reasoning about a design artifact and generating programming support.

3.2. Integrating Non-Functional Concerns into Software Design

Most existing design approaches do not address non-functional concerns. When they do, they do not provide an approach to non-functional concerns that covers the entire development life-cycle. Furthermore, they usually are general purpose, impeding the use of non-functional declarations for verification and code generation. For example, the Architecture Analysis & Design Language (AADL) is a standard dedicated to real-time embedded systems [28]. AADL provides language constructs for the specification of software systems (*e.g.,* component, port) and their deployment on execution platforms (*e.g.,* thread, process, memory). Using AADL, designers specify non-functional aspects by adding properties on language constructs (*e.g.,* the period of a thread) or using language extensions such as the Error Model Annex. [1] The software design concepts of AADL are still rather general purpose and give little guidance to the designer.

Beyond offering a conceptual framework, our language-based approach provides an ideal setting to address non-functional properties (*e.g.,* performance, reliability, security, ...). Specifically, a design language can be enriched with non-functional declarations to pursue two goals: (1) expanding further the type of conformance that can be checked between the design of a software system and its implementation, and (2) enabling additional programming support and guidance.

We are investigating this idea by extending our design language with non-functional declarations. For example, we have addressed error handling [10], access conflicts to resources [30], and quality of service constraints [29].

[1] The Error Model Annex is a standardized AADL extension for the description of errors [34].

Following our approach to paradigm-oriented software development, non-functional declarations are verified at design time, they generate support that guides and constrains programming, they produce a runtime system that preserves invariants.

3.3. Human-driven Software Design

Knowledge of the human characteristics (individual, social and organizational) allow the design of complex system and artifacts for increasing their efficacy. In our approach of assistive computing, a main challenge is the integration of facets of Human Factors in order to design technology support adapted to user needs in term of ergonomic properties (acceptability, usability, utility etc) and delivered functionalities (oriented task under user abilities contraints).

We adapt this approach to improve the independent living and self-determination of users with cognitive impairments by developing a variety of orchestration scenarios of networked objects (hardware/software) to provide a pervasive support to their activities. Human factors methodologies are adopted in our approach with the direct purpose the reliability and efficiency of the performance of digital support systems in respect of objectives of health and well-being of the person (monitoring, evaluation, and rehabilitation).

Precisely, our methodologies are based on a closed iterative loop, as described in the figure below :

- Identifying the person needs in a natural situation (i.e. , desired but problematic activities) according to Human Factors Models of activity (i.e., environmental constraints; social support networks - caregivers and family; person's abilities)
- Design pro- against - environmental measures that will being support the digital assistance to bypass cognitive impairment (ie , according to environmental models of cognitive compensatory mechanisms); and then develop solutions in terms of technological support (scenarios of networked objects, hardware interface, software interface , interaction style, etc)
- Empirical evaluation based on human experimentations that includes ergonomic assessments (acceptability , usability , usefulness, etc) as well as longitudinal evaluations of use's efficacy in terms of activities performed by the individual, of satisfaction and well -being provided to the individual but also to his/her entourage (family and caregivers).

`../../../../projets/phoenix/IMG/UserCentredApproach.p`

Figure 1. User-Centred Approach

RMOD Project-Team

3. Research Program

3.1. Software Reengineering

Strong coupling among the parts of an application severely hampers its evolution. Therefore, it is crucial to answer the following questions: How to support the substitution of certain parts while limiting the impact on others? How to identify reusable parts? How to modularize an object-oriented application?

Having good classes does not imply a good application layering, absence of cycles between packages and reuse of well-identified parts. Which notion of cohesion makes sense in presence of late-binding and programming frameworks? Indeed, frameworks define a context that can be extended by subclassing or composition: in this case, packages can have a low cohesion without being a problem for evolution. How to obtain algorithms that can be used on real cases? Which criteria should be selected for a given remodularization?

To help us answer these questions, we work on enriching Moose, our reengineering environment, with a new set of analyses [55], [54]. We decompose our approach in three main and potentially overlapping steps:

1. Tools for understanding applications,
2. Remodularization analyses,
3. Software Quality.

3.1.1. Tools for understanding applications

Context and Problems. We are studying the problems raised by the understanding of applications at a larger level of granularity such as packages or modules. We want to develop a set of conceptual tools to support this understanding.

Some approaches based on Formal Concept Analysis (FCA) [83] show that such an analysis can be used to identify modules. However the presented examples are too small and not representative of real code.

Research Agenda.

FCA provides an important approach in software reengineering for software understanding, design anomalies detection and correction, but it suffers from two problems: (i) it produces lattices that must be interpreted by the user according to his/her understanding of the technique and different elements of the graph; and, (ii) the lattice can rapidly become so big that one is overwhelmed by the mass of information and possibilities [42]. We look for solutions to help people putting FCA to real use.

3.1.2. Remodularization analyses

Context and Problems. It is a well-known practice to layer applications with bottom layers being more stable than top layers [71]. Until now, few works have attempted to identify layers in practice: Mudpie [85] is a first cut at identifying cycles between packages as well as package groups potentially representing layers. DSM (dependency structure matrix) [84], [79] seems to be adapted for such a task but there is no serious empirical experience that validates this claim. From the side of remodularization algorithms, many were defined for procedural languages [67]. However, object-oriented programming languages bring some specific problems linked with late-binding and the fact that a package does not have to be systematically cohesive since it can be an extension of another one [86], [58].

As we are designing and evaluating algorithms and analyses to remodularize applications, we also need a way to understand and assess the results we are obtaining.

Research Agenda. We work on the following items:

Layer identification. We propose an approach to identify layers based on a semi-automatic classification of package and class interrelationships that they contain. However, taking into account the wish or knowledge of the designer or maintainer should be supported.

Cohesion Metric Assessment. We are building a validation framework for cohesion/coupling metrics to determine whether they actually measure what they promise to. We are also compiling a number of traditional metrics for cohesion and coupling quality metrics to evaluate their relevance in a software quality setting.

3.1.3. Software Quality

Research Agenda. Since software quality is fuzzy by definition and a lot of parameters should be taken into account we consider that defining precisely a unique notion of software quality is definitively a Grail in the realm of software engineering. The question is still relevant and important. We work on the two following items:

Quality models. We studied existing quality models and the different options to combine indicators — often, software quality models happily combine metrics, but at the price of losing the explicit relationships between the indicator contributions. There is a need to combine the results of one metric over all the software components of a system, and there is also the need to combine different metric results for any software component. Different combination methods are possible that can give very different results. It is therefore important to understand the characteristics of each method.

Bug prevention. Another aspect of software quality is validating or monitoring the source code to avoid the apparition of well known sources of errors and bugs. We work on how to best identify such common errors, by trying to identify earlier markers of possible errors, or by helping identifying common errors that programmers did in the past.

3.2. Language Constructs for Modular Design

While the previous axis focuses on how to help remodularizing existing software, this second research axis aims at providing new language constructs to build more flexible and recomposable software. We will build on our work on traits [81], [56] and classboxes [43] but also start to work on new areas such as isolation in dynamic languages. We will work on the following points: (1) Traits and (2) Modularization as a support for isolation.

3.2.1. Traits-based program reuse

Context and Problems. Inheritance is well-known and accepted as a mechanism for reuse in object-oriented languages. Unfortunately, due to the coarse granularity of inheritance, it may be difficult to decompose an application into an optimal class hierarchy that maximizes software reuse. Existing schemes based on single inheritance, multiple inheritance, or mixins, all pose numerous problems for reuse.

To overcome these problems, we designed a new composition mechanism called Traits [81], [56]. Traits are pure units of behavior that can be composed to form classes or other traits. The trait composition mechanism is an alternative to multiple or mixin inheritance in which the composer has full control over the trait composition. The result enables more reuse than single inheritance without introducing the drawbacks of multiple or mixin inheritance. Several extensions of the model have been proposed [53], [75], [44], [57] and several type systems were defined [59], [82], [76], [69].

Traits are reusable building blocks that can be explicitly composed to share methods across unrelated class hierarchies. In their original form, traits do not contain state and cannot express visibility control for methods. Two extensions, stateful traits and freezable traits, have been proposed to overcome these limitations. However, these extensions are complex both to use for software developers and to implement for language designers.

Research Agenda: Towards a pure trait language. We plan distinct actions: (1) a large application of traits, (2) assessment of the existing trait models and (3) bootstrapping a pure trait language.

- To evaluate the expressiveness of traits, some hierarchies were refactored, showing code reuse [46]. However, such large refactorings, while valuable, may not exhibit all possible composition problems, since the hierarchies were previously expressed using single inheritance and following certain patterns. We want to redesign from scratch the collection library of Smalltalk (or part of it). Such a redesign should on the one hand demonstrate the added value of traits on a real large and redesigned library and on the other hand foster new ideas for the bootstrapping of a pure trait-based language.

  In particular we want to reconsider the different models proposed (stateless [56], stateful [45], and freezable [57]) and their operators. We will compare these models by (1) implementing a trait-based collection hierarchy, (2) analyzing several existing applications that exhibit the need for traits. Traits may be flattened [74]. This is a fundamental property that confers to traits their simplicity and expressiveness over Eiffel's multiple inheritance. Keeping these aspects is one of our priority in forthcoming enhancements of traits.
- Alternative trait models. This work revisits the problem of adding state and visibility control to traits. Rather than extending the original trait model with additional operations, we use a fundamentally different approach by allowing traits to be lexically nested within other modules. This enables traits to express (shared) state and visibility control by hiding variables or methods in their lexical scope. Although the traits' "flattening property" no longer holds when they can be lexically nested, the combination of traits with lexical nesting results in a simple and more expressive trait model. We formally specify the operational semantics of this combination. Lexically nested traits are fully implemented in AmbientTalk, where they are used among others in the development of a Morphic-like UI framework.
- We want to evaluate how inheritance can be replaced by traits to form a new object model. For this purpose we will design a minimal reflective kernel, inspired first from ObjVlisp [51] then from Smalltalk [62].

3.2.2. Reconciling Dynamic Languages and Isolation

Context and Problems. More and more applications require dynamic behavior such as modification of their own execution (often implemented using reflective features [66]). For example, F-script allows one to script Cocoa Mac-OS X applications and Lua is used in Adobe Photoshop. Now in addition more and more applications are updated on the fly, potentially loading untrusted or broken code, which may be problematic for the system if the application is not properly isolated. Bytecode checking and static code analysis are used to enable isolation, but such approaches do not really work in presence of dynamic languages and reflective features. Therefore there is a tension between the need for flexibility and isolation.

Research Agenda: Isolation in dynamic and reflective languages. To solve this tension, we will work on *Sure*, a language where isolation is provided by construction: as an example, if the language does not offer field access and its reflective facilities are controlled, then the possibility to access and modify private data is controlled. In this context, layering and modularizing the meta-level [47], as well as controlling the access to reflective features [48], [49] are important challenges. We plan to:

- Study the isolation abstractions available in erights (http://www.erights.org) [73], [72], and Java's class loader strategies [68], [63].
- Categorize the different reflective features of languages such as CLOS [65], Python and Smalltalk [77] and identify suitable isolation mechanisms and infrastructure [60].
- Assess different isolation models (access rights, capabilities [78]...) and identify the ones adapted to our context as well as different access and right propagation.
- Define a language based on
  - the decomposition and restructuring of the reflective features [47],

- the use encapsulation policies as a basis to restrict the interfaces of the controlled objects [80],
- the definition of method modifiers to support controlling encapsulation in the context of dynamic languages.

An open question is whether, instead of providing restricted interfaces, we could use traits to grant additional behavior to specific instances: without trait application, the instances would only exhibit default public behavior, but with additional traits applied, the instances would get extra behavior. We will develop *Sure*, a modular extension of the reflective kernel of Smalltalk (since it is one of the languages offering the largest set of reflective features such as pointer swapping, class changing, class definition...) [77].

TRISKELL Project-Team

3. Research Program

3.1. Model Driven Engineering for Distributed Software

Objects, design patterns, software components, contracts, aspects, models, UML, product lines

3.1.1. Software Product Lines

It is seldom the case nowadays that we can any longer deliver software systems with the assumption that one-size-fits-all. We have to handle many variants accounting not only for differences in product functionalities (range of products to be marketed at different prices), but also for differences in hardware (e.g.; graphic cards, display capacities, input devices), operating systems, localization, user preferences for GUI ("skins"). Obvioulsy, we do not want to develop from scratch and independantly all of the variants the marketing department wants. Furthermore, all of these variant may have many successive versions, leading to a two-dimensional vision of product-lines.

3.1.2. Object-Oriented Software Engineering

The object-oriented approach is now widespread for the analysis, the design, and the implementation of software systems. Rooted in the idea of modeling (through its origin in Simula), object-oriented analysis, design and implementation takes into account the incremental, iterative and evolutive nature of software development [80], [78]: large software system are seldom developed from scratch, and maintenance activities represent a large share of the overall development effort.

In the object-oriented standard approach, objects are instances of classes. A class encapsulates a single abstraction in a modular way. A class is both *closed*, in the sense that it can be readily instanciated and used by clients objects, and *open*, that is subject to extensions through inheritance [82].

3.1.3. Design Pattern

Since by definition objects are simple to design and understand, complexity in an object-oriented system is well known to be in the *collaboration* between objects, and large systems cannot be understood at the level of classes and objects. Still these complex collaborations are made of recurring patterns, called design patterns. The idea of systematically identifying and documenting design patterns as autonomous entities was born in the late 80's. It was brought into the mainstream by such people as Beck, Ward, Coplien, Booch, Kerth, Johnson, etc. (known as the Hillside Group). However the main event in this emerging field was the publication, in 1995, of the book *Design Patterns: Elements of Reusable Object Oriented Software* by the so-called Gang of Four (GoF), that is E. Gamma, R. Helm, R. Johnson and J. Vlissides [79]. Today, design patterns are widely accepted as useful tools for guiding and documenting the design of object-oriented software systems. Design patterns play many roles in the development process. They provide a common vocabulary for design, they reduce system complexity by naming and defining abstractions, they constitute a base of experience for building reusable software, and they act as building blocks from which more complex designs can be built. Design patterns can be considered reusable micro-architectures that contribute to an overall system architecture. Ideally, they capture the intent behind a design by identifying the component objects, their collaborations, and the distribution of responsibilities. One of the challenges addressed in the Triskell project is to develop concepts and tools to allow their formal description and their automatic application.

3.1.4. Component

The object concept also provides the basis for *software components*, for which Szyperski's definition [88] is now generally accepted, at least in the industry:

> *A software component is a unit of composition with contractually specified interfaces and explicit context dependencies only. A software component can be deployed independently and is subject to composition by third party.*

Component based software relies on assemblies of components. Such assemblies rely in turn on fundamental mechanisms such as precise definitions of the mutual responsability of partner components, interaction means between components and their non-component environment and runtime support (e.g. .Net, EJB, Corba Component Model CCM, OSGI or Fractal).

Components help reducing costs by allowing reuse of application frameworks and components instead of redeveloping applications from scratch (product line approach). But more important, components offer the possibility to radically change the behaviors and services offered by an application by substitution or addition of new components, even a long time after deployment. This has a major impact of software lifecycle, which should now handle activities such as the design of component frameworks, the design of reusable components as deployment units, the validation of component compositions coming from various origins and the component life-cycle management.

Empirical methods without real component composition models have appeared during the emergence of a real component industry (at least in the Windows world). These methods are now clearly the cause of untractable validation and of integration problems that can not be transposed to more critical systems (see for example the accidental destruction of Ariane 501 [81]).

Providing solutions for formal component composition models and for verifiable quality (notion of *trusted components*) are especially relevant challenges. Also the methodological impact of component-based development (for example within the maturity model defined by the SEI) is also worth attention.

3.1.5. Contracts

Central to this trusted component notion is the idea of *contract*. A software contract captures mutual requirements and benefits among stake-holder components, for example between the client of a service and its suppliers (including subcomponents). Contracts strengthen and deepen interface specifications. Along the lines of abstract data type theory, a common way of specifying software contracts is to use boolean assertions called pre- and post-conditions for each service offered, as well as class invariants for defining general consistency properties. Then the contract reads as follows: The client should only ask a supplier for a service in a state where the class invariant and the precondition of the service are respected. In return, the supplier promises that the work specified in the post-condition will be done, and the class invariant is still respected. In this way rights and obligations of both client and supplier are clearly delineated, along with their responsibilities. This idea was first implemented in the Eiffel language [83] under the name *Design by Contract*, and is now available with a range of expressive power into several other programming languages (such as Java) and even in the Unified Modeling Language (UML) with the Object Constraint Language (OCL) [89]. However, the classical predicate based contracts are not enough to describe the requirements of modern applications. Those applications are distributed, interactive and they rely on resources with random quality of service. We have shown that classical contracts can be extended to take care of synchronization and extrafunctional properties of services (such as throughput, delays, etc) [77].

3.1.6. Models and Aspects

As in other sciences, we are increasingly resorting to modelling to master the complexity of modern software development. According to Jeff Rothenberg,

> *Modeling, in the broadest sense, is the cost-effective use of something in place of something else for some cognitive purpose. It allows us to use something that is simpler, safer or cheaper than reality instead of reality for some purpose. A model represents reality for the given purpose; the model is an abstraction of reality in the sense that it cannot represent all aspects of reality. This allows us to deal with the world in a simplified manner, avoiding the complexity, danger and irreversibility of reality.*

So modeling is not just about expressing a solution at a higher abstraction level than code. This has been useful in the past (assembly languages abstracting away from machine code, 3GL abstracting over assembly languages, etc.) and it is still useful today to get a holistic view on a large C++ program. But modeling goes well beyond that.

Modeling is indeed one of the touchstone of any scientific activity (along with validating models with respect to experiments carried out in the real world). Note by the way that the specificity of engineering is that engineers build models of artefacts that usually do not exist yet (with the ultimate goal of building them).

In engineering, one wants to break down a complex system into as many models as needed in order to address all the relevant concerns in such a way that they become understandable enough. These models may be expressed with a general purpose modeling language such as the Unified Modeling Language (UML), or with Domain Specific Languages when it is more appropriate.

Each of these models can be seen as the abstraction of an aspect of reality for handling a given concern. The provision of effective means for handling such concerns makes it possible to establish critical trade-offs early on in the software life cycle, and to effectively manage variation points in the case of product-lines.

Note that in the Aspect Oriented Programming community, the notion of aspect is defined in a slightly more restricted way as the modularization of a cross-cutting concern. If we indeed have an already existing “main” decomposition paradigm (such as object orientation), there are many classes of concerns for which clear allocation into modules is not possible (hence the name “cross-cutting”). Examples include both allocating responsibility for providing certain kinds of functionality (such as login) in a cohesive, loosely coupled fashion, as well as handling many non-functional requirements that are inherently cross-cutting e.g.; security, mobility, availability, distribution, resource management and real-time constraints.

However now that aspects become also popular outside of the mere programming world [87], there is a growing acceptance for a wider definition where an aspect is a concern that can be modularized. The motivation of these efforts is the systematic identification, modularization, representation, and composition of these concerns, with the ultimate goal of improving our ability to reason about the problem domain and the corresponding solution, reducing the size of software model and application code, development costs and maintenance time.

3.1.7. Design and Aspect Weaving

So really modeling is the activity of separating concerns in the problem domain, an activity also called *analysis*. If solutions to these concerns can be described as aspects, the design process can then be characterized as a weaving of these aspects into a detailed design model (also called the solution space). This is not new: this is actually what designers have been effectively doing forever. Most often however, the various aspects are not *explicit*, or when there are, it is in the form of informal descriptions. So the task of the designer is to do the weaving in her head more or less at once, and then produce the resulting detailed design as a big tangled program (even if one decomposition paradigm, such as functional or object-oriented, is used). While it works pretty well for small problems, it can become a major headache for bigger ones.

Note that the real challenge here is not on how to design the system to take a particular aspect into account: there is a huge design know-how in industry for that, often captured in the form of Design Patterns (see above). Taking into account more than one aspect as the same time is a little bit more tricky, but many large scale successful projects in industry are there to show us that engineers do ultimately manage to sort it out.

The real challenge in a product-line context is that the engineer wants to be able to change her mind on which version of which variant of any particular aspect she wants in the system. And she wants to do it cheaply, quickly and safely. For that, redoing by hand the tedious weaving of every aspect is not an option.

3.1.8. Model Driven Engineering

Usually in science, a model has a different nature that the thing it models ("do not take the map for the reality" as Sun Tse put it many centuries ago). Only in software and in linguistics a model has the same nature as the thing it models. In software at least, this opens the possibility to automatically derive software from its model. This property is well known from any compiler writer (and others), but it was recently made quite popular with an OMG initiative called the Model Driven Architecture (MDA). This requires that models are no longer informal, and that the weaving process is itself described as a program (which is as a matter of facts an executable meta-model) manipulating these models to produce a detailed design that can ultimately be transformed to code or at least test suites.

The OMG has built a meta-data management framework to support the MDA. It is mainly based on a unique M3 “meta-meta-model” called the Meta-Object Facility (MOF) and a library of M2 meta-models, such as the UML (or SPEM for software process engineering), in which the user can base his M1 model.

The MDA core idea is that it should be possible to capitalize on platform-independent models (PIM), and more or less automatically derive platform-specific models (PSM) –and ultimately code– from PIM through model transformations. But in some business areas involving fault-tolerant, distributed real-time computations, there is a growing concern that the added value of a company not only lies in its know-how of the business domain (the PIM) but also in the design know-how needed to make these systems work in the field (the transformation to go from PIM to PSM). Reasons making it complex to go from a simple and stable business model to a complex implementation include:

- Various modeling languages used beyond UML,
- As many points of views as stakeholders,
- Deliver software for (many) variants of a platform,
- Heterogeneity is the rule,
- Reuse technical solutions across large product lines (e.g. fault tolerance, security, etc.),
- Customize generic transformations,
- Compose reusable transformations,
- Evolve and maintain transformations for 15+ years.

This wider context is now known as Model Driven Engineering.

COATI Project-Team

3. Research Program

3.1. Research Program

Members of COATI have a good expertise in the design and management of wired and wireless backbone, backhaul, broadband, and complex networks. On the one hand, we cope with specific problems such as energy efficiency in backhaul and backbone networks, routing reconfiguration in connection oriented networks (MPLS, WDM), traffic agregation in SONET networks, compact routing in large-scale networks, survivability to single and multiple failures, etc. These specific problems often come from questions of our industrial partners. On the other hand, we study fondamental problems mainly related to routing and reliability that appear in many networks (not restricted to our main fields of applications) and that have been widely studied in the past. However, previous solutions do not take into account the constraints of current networks/traffic such as their huge size and their dynamics. COATI thus puts a significant research effort in the following directions:

- **Energy efficiency** at both the design and management levels. More precisely, we plan to develop accurate modeling of the power consumption of various parts and components of the networks through measurement done in collaboration with industrial partners (Alcatel-Lucent, 3Roam, Orange labs, etc.). Then, we shall propose new designs of the networks and new routing algorithms in order to lower the power consumption.
- **Larger networks:** Another challenge one has to face is the increase in size of practical instances. It is already difficult, if not impossible, to solve practical instances optimally using existing tools. Therefore, we will have to find new ways to solve problems using reduction and decomposition methods, characterization of polynomial instances (which are surprisingly often the practical ones), or algorithms with acceptable practical performances.
- **Stochastic behaviors:** Larger topologies mean frequent changes due to traffic and radio fluctuations, failures, maintenance operations, growth, routing policy changes, etc. We aim at including these stochastic behaviors in our combinatorial optimization process to handle the dynamics of the system and to obtain robust designs of networks.

DANTE Team

3. Research Program

3.1. Graph-based signal processing

Participants: Christophe Crespelle, Éric Fleury, Paulo Gonçalves, Márton Karsai, Benjamin Girault.

Evolving networks can be regarded as "*out of equilibrium*" systems. Indeed, their dynamics is typically characterized by non standard and intricate statistical properties, such as non-stationarity, long range memory effects, intricate space and time correlations.

Analysing, modelling, and even defining adapted concepts for dynamic graphs is at the heart of DANTE. This is a largely open question that has to be answered by keeping a balance between specificity (solutions triggered by specific data sets) and generality (universal approaches disconnected from social realities). We will tackle this challenge from a graph-based signal processing perspective involving signal analysts and computer scientists, together with experts of the data domain application. One can distinguish two different issues in this challenge, one related to the graph-based organisation of the data and the other to the time dependency that naturally exits in the dynamic graph object. In both cases, a number of contributions can be found in the literature, albeit in different contexts. In our application domain, high-dimensional data "naturally reside" on the vertices of weighted graphs. The emerging field of signal processing on graphs merges algebraic and spectral graph theoretic concepts with computational harmonic analysis to process such signals on graphs [48].

As for the first point, adapting well-founded signal processing techniques to data represented as graphs is an emerging, yet quickly developing field which has already received key contributions. Some of them are very general and delineate ambitious programs aimed at defining universal, generally unsupervised methods for exploring high-dimensional data sets and processing them. This is the case for instance of the « diffusion wavelets » and « diffusion maps » pushed forward at Yale and Duke [33]. Others are more traditionally connected with standard signal processing concepts, in the spirit of elaborating new methodologies via some bridging between networks and time series, see, *e.g.*, ([43] and references therein). Other viewpoints can be found as well, including multi-resolution Markov models [51], Bayesian networks or distributed processing over sensor networks [42]. Such approaches can be particularly successful for handling static graphs and unveiling aspects of their organisation in terms of dependencies between nodes, grouping, etc. Incorporating possible time dependencies within the whole picture calls however for the addition of an extra dimension to the problem "as it would be the case when switching from one image to a video sequence", a situation for which one can imagine to take advantage of the whole body of knowledge attached to non-stationary signal processing [34].

3.2. Theory and Structural Dynamic Properties of dynamic Networks

Participants: Christophe Crespelle, Éric Fleury, Anthony Busson, Márton Karsai.

Characterization of the dynamics of complex networks. We need to focus on intrinsic properties of evolving/dynamic complex networks. New notions (as opposed to classical static graph properties) have to be introduced: rate of vertices or links appearances or disappearances, the duration of link presences or absences. Moreover, more specific properties related to the dynamics have to be defined and are somehow related to the way to model a dynamic graph.

Through the systematic analysis and characterisation of static network representations of many different systems, researchers of several disciplines have unveiled complex topologies and heterogeneous structures, with connectivity patterns statistically characterised by heavy-tails and large fluctuations, scale-free properties and non trivial correlations such as high clustering and hierarchical ordering [45]. A large amount of work has been devoted to the development of new tools for statistical characterisation and modelling of networks, in order to identify their most relevant properties, and to understand which growth mechanisms could lead to these properties. Most of those contributions have focused on static graphs or on dynamic process (*e.g.* diffusion) occurring on static graphs. This has called forth a major effort in developing the methodology to characterise the topology and temporal behaviour of complex networks [45], [36], [52], [41], to describe the observed structural and temporal heterogeneities [28], [36], [29], to detect and measure emerging community structures [35], [49], [50], to see how the functionality of networks determines their evolving structure [40], and to determine what kinds of correlations play a role in their dynamics [37], [39], [44].

The challenge is now to extend this kind of statistical characterisation to dynamical graphs. In other words, links in dynamic networks are temporal events, called contacts, which can be either punctual or last for some period of time. Because of the complexity of this analysis, the temporal dimension of the network is often ignored or only roughly considered. Therefore, fully taking into account the dynamics of the links into a network is a crucial and highly challenging issue.

Another powerful approach to model time-varying graphs is via activity driven network models. In this case the bottom line assumption is taken only about the distribution of activity rates of interacting entities. The activity rate is realistically broadly distributed and refers to the probability that an entity becomes active and creates a connection with another entity within a unite time step [47]. Even the generic model is already capable to recover some realistic features of the emerging graph, its main advantage is to provide a general framework to study various type of correlations present in real temporal networks. By synthesising such correlations (*e.g.* memory effects, preferential attachment, triangular closing mechanisms, ...) from the real data, we are able to extend the general mechanism and receive a temporal network model, which shows certain realistic feature in a controlled way. This can be used to study the effect of selected correlations on the evolution of the emerging structure [38] and its co-evolution with ongoing processes like spreading phenomena, synchronisation, evolution of consensus, random walk etc. [38], [46]. This approach allows also to develop control and immunisation strategies by fully considering the temporal nature of the backgrounding network.

3.3. Distributed Algorithms for dynamic networks: regulation, adaptation and interaction

Participants: Thomas Begin, Anthony Busson, Paulo Gonçalves, Isabelle Guérin Lassous.

Dedicated algorithms for dynamic networks. First, the dynamic network object itself trigger original algorithmic questions. It mainly concerns distributed algorithms that should be designed and deployed to efficiently measure the object itself and get an accurate view of its dynamic behaviour. Such distributed measure should be "transparent", that is, it should not introduce bias or at least it should be controllable and corrigible. Such problem is encountered in all distributed metrology measures / distributed sondes: P2P, sensor network, wireless network, QoS routing... This question raises naturally the intrinsic notion of adaptation and control of the dynamic network itself since it appears that autonomous networks and traffic aware routing are becoming crucial.

A case in the point for dynamic networks are communication networks which are known to potentially undergo high dynamicity. The dynamicity exhibited by these networks results from several factors including, for instance, changes in the topology and varying workload conditions. Although most implemented protocols and existing solutions in the literature can cope with a dynamic behaviour, the evolution of their behaviour operate identically whatever the actual properties of the dynamicity. For instance, parameters of the routing protocols (*e.g.* hello packets transmission frequency) or routing methods (*e.g.* reactive / proactive) are commonly hold constant regardless of the nodes mobility. Similarly, the algorithms ruling CSMA/CA (*e.g.* size of the contention window) are tuned identically and they do not change according to the actual workload and observed topology.

Dynamicity in computer networks tends to affect a large number of performance parameters (if not all) coming from various layers (viz. physical, link, routing and transport). To find out which ones matters the most for our intended purpose, we expect to rely on the tools developed by the two former axis. These quantities should capture and characterise the actual network dynamicity. Our goal is to take advantage of this latter information in order to refine existing protocols, or even to propose new solutions. More precisely, we will attempt to associate "fundamental" changes occurring in the underlying graph of a network (reported through graph-based signal tools) to quantitative performance that are matter of interests for networking applications and the end-users. We expect to rely on available testbeds such as Senslab and FIT to experiment our solutions and ultimately validate our approach.

DIANA Team

3. Research Program

3.1. Experimental approach to Networking

The main consequence of the complexity of the Internet is that modeling and understanding the network and services are harder and harder to achieve. Our team has an experimental approach built around measurements and observation of the current behavior of Internet users and available technology and come up with models for the ways information are exchanged. Then we will design and evaluate protocols and system solutions that allow this seamless, open, efficient, and secure access to information and services. We will in particular focus on whether to follow a clean-slate approach or leverage on existing technologies towards the solutions of the above two challenges. Evaluation of our proposals will be performed by leveraging on networking platforms and simulators developed by the team such as OneLab, FIT and ns-3.

We develop experimental code to evaluate the ideas we propose. As an example, we developed recently the Meddle platform to address the problem of opaqueness and lack of control on the Internet. Meddle uses traffic indirection to diagnose mobile devices independently of the OS, ISP, and access technology. We used the platform to observe personal information leakages by popular iOS and Android applications. We also used it to analyze in detail the network characteristics of video streaming services, the most popular Web-service in the current Internet.

3.2. User Centric Networking

Billions of people are using the Inernet with different levels of satisfaction concerning the performance. This means that the past research challenges such as efficiency and scalability of Internet protocols are no longer perceived by the users as important challenges to address. However, as the number of Internet devices and bandwidth requirements continue to explode, they still need to be addressed and represent mandatory properties of any new protocol proposed. Apart those well-known research problems, new research challenges are appearing on the design of services centered on the user needs. Thus, we envision a shift from network-centric research challenges to user-centric networking research challenges.

The main consequence of the Internet complexity for the users is the opacity. Users do not have any way to understand and control what their Internet services are doing, which clearly violate their citizen rights. We are witnessing currently a strong interest of Internet providers in this domain along with a growing number of projects funded by service providers (such as Google or Microsoft) on transparency. We define in the following two different rights that we consider as the ones to be addressed for the next decade. DIANA will articulate its research effort around these two rights.

- **Service transparency**

  The first consequence of Internet complexity is its opacity. The second consequence is the non-predictability of the quality it offers to end-users. It is fundamental for users to be aware of what is going-on on their Internet access and to evaluate the quality they are experiencing, or they can expect, in terms of the different applications they run. For that, some fundamental questions must be answered: What quality can I expect from my Internet access? Why is my service not running properly? Are there any private data sent on the Internet and where? Whereas these questions could be answered with classical measurement techniques (such as ping, traceroute, and tcpdump) in the past, they are vastly more complex today. Indeed, nowadays, mobile device providers, applications/services designers and mobile operators all have conflicting interests and no incentive for real transparency. Regular measurement techniques are either blocked (e.g., traceroutes are blocked by mobile providers to prevent topology discovery which is considered as an industrial secret) or impossible (e.g., tcpdump cannot run on mobile devices because the necessary APIs are not exposed to the application programmer, or simply not implemented in the device drivers). As a consequence, new dedicated measurement platforms are required to work around the existing limitations, and in particular (i) to reveal the reality of the network behind our device and the services we connect to, (ii) to shed light on the quality we can expect from our access in terms of the different applications we run, and (iii) in case of a problem, to help the end user diagnosing its root causes. For instance, to diagnose privacy leaks, we need to perform OS instrumentation and build dedicated experimental platforms to break SSL encryption widely used by services to hide their functioning.

- **Open content access, sharing and control**

  Users must, at any time, keep the control on their content, that is, seamlessly retrieve them and control who can access them. Today proprietary solutions, such as Google Drive or iCloud, partially solve the problem of accessing content seamlessly on heterogeneous devices, but at the cost of losing control on them. However, several important questions must be answered in this context: where my data is localized physically, who has the right to access my confidential documents, who has actually accessed my photos, how can I be sure that this document is permanently deleted? Having an open access (i.e., independent of a specific vendor) and the possibility to control who is accessing content must be a fundamental right. This means that whatever the device, the operating system, the location, and the available Internet provider, users have the right to seamlessly and efficiently access their content without losing control on them. Protecting users from service misbehaviors and privacy leaks is a difficult task because it requires sophisticated and deployable architectural modifications. One example is the case of a poor video streaming quality. Whereas video streaming is today the most popular application (in terms of aggregate traffic) in the Internet, it is hard for a user to diagnose and solve issues because Internet actors (ISPs and service providers) have conflicting interests and no reason to collaborate. A vivid example is the one of Free, a French ISP, which is limiting the throughput for YouTube streams in order to put pressure on Google to compensate the ISP investments. This is clearly against the citizen rights, and it requires working around the throughput limitations using a dedicated and open indirection infrastructure. Another example is the one of the free application market. Most of free applications embed advertisements that are operated by third parties. Whereas most applications do not need to send data on the Internet, private information are leaked in order to run targeted advertisements only. This issue cannot be solved with simple ad-blocking on the device, because the operating system of mobile devices does not allow interposing on applications behavior. Also, blindly blocking all ads might challenge the market of free applications. The only solution is to build a dedicated open infrastructure that filters out private information while still making the business of targeted advertisement possible.

DIONYSOS Project-Team

3. Research Program

3.1. Introduction

The scientific foundations of our work are those of network design and network analysis. Specifically, this concerns the principles of packet switching and in particular of IP networks (protocol design, protocol testing, routing, scheduling techniques), and the mathematical and algorithmic aspects of the associated problems, on which our methods and tools are based.

These foundations are described in the following paragraphs. We begin by a subsection dedicated to Quality of Service (QoS) and Quality of Experience (QoE), since they can be seen as unifying concepts in our activities. Then we briefly describe the specific sub-area of model evaluation and about the particular multidisciplinary domain of network economics.

3.2. Quality of Service and Quality of Experience

Since it is difficult to develop as many communication solutions as possible applications, the scientific and technological communities aim towards providing general *services* allowing to give to each application or user a set of properties nowadays called "Quality of Service" (QoS), a terminology lacking a precise definition. This QoS concept takes different forms according to the type of communication service and the aspects which matter for a given application: for performance it comes through specific metrics (delays, jitter, throughput, etc.), for dependability it also comes through appropriate metrics: reliability, availability, or vulnerability, in the case for instance of WAN (Wide Area Network) topologies, etc.

QoS is at the heart of our research activities: We look for methods to obtain specific "levels" of QoS and for techniques to evaluate the associated metrics. Our ultimate goal is to provide tools (mathematical tools and/or algorithms, under appropriate software "containers" or not) allowing users and/or applications to attain specific levels of QoS, or to improve the provided QoS, if we think of a particular system, with an optimal use of the resources available. Obtaining a good QoS level is a very general objective. It leads to many different areas, depending on the systems, applications and specific goals being considered. Our team works on several of these areas. We also investigate the impact of network QoS on multimedia payloads to reduce the impact of congestion.

Some important aspects of the behavior of modern communication systems have subjective components: the quality of a video stream or an audio signal, *as perceived by the user*, is related to some of the previous mentioned parameters (packet loss, delays, ...) but in an extremely complex way. We are interested in analyzing these types of flows from this user-oriented point of view. We focus on the *user perceived quality*, the main component of what is nowadays called Quality of Experience (in short, QoE), to underline the fact that, in this case, we want to center the analysis on the user. In this context, we have a global project called PSQA, which stands for Pseudo-Subjective Quality Assessment, and which refers to a methodology allowing to automatically measure QoE (see 3.2).

Another special case to which we devote research efforts in the team is the analysis of qualitative properties related to interoperability assessment. This refers to the act of determining if end-to-end functionality between at least two communicating systems is as required by the base standards for those systems. Conformance is the act of determining to what extent a single component conforms to the individual requirements of the standard it is based on. Our purpose is to provide such a formal framework (methods, algorithms and tools) for interoperability assessment, in order to help in obtaining efficient interoperability test suites for new generation networks, mainly around IPv6-related protocols. The interoperability test suites generation is based on specifications (standards and/or RFCs) of network components and protocols to be tested.

3.3. Stochastic modeling

The scientific foundations of our modeling activities are composed of stochastic processes theory and, in particular, Markov processes, queuing theory, stochastic graphs theory, etc. The objectives are either to develop numerical solutions, or analytical ones, or possibly discrete event simulation or Monte Carlo (and Quasi-Monte Carlo) techniques. We are always interested in model evaluation techniques for dependability and performability analysis, both in static (network reliability) and dynamic contexts (depending on the fact that time plays an explicit role in the analysis or not). We look at systems from the classical so-called *call level*, leading to standard models (for instance, queues or networks of queues) and also at the *burst level*, leading to *fluid models*.

In recent years, our work on the design of the topologies of WANs led us to optimization techniques, in particular in the case of very large optimization problems, usually formulated in terms of graphs. The associated methods we are interested in are composed of simulated annealing, genetic algorithms, TABU search, etc. For the time being, we have obtained our best results with GRASP techniques.

Network pricing is a good example of a multi-disciplinary research activity half-way between applied mathematics, economy and networking, centered on stochastic modeling issues. Indeed, the Internet is facing a tremendous increase of its traffic volume. As a consequence, real users complain that large data transfers take too long, without any possibility to improve this by themselves (by paying more, for instance). A possible solution to cope with congestion is to increase the link capacities; however, many authors consider that this is not a viable solution as the network must respond to an increasing demand (and experience has shown that demand of bandwidth has always been ahead of supply), especially now that the Internet is becoming a commercial network. Furthermore, incentives for a fair utilization between customers are not included in the current Internet. For these reasons, it has been suggested that the current flat-rate fees, where customers pay a subscription and obtain an unlimited usage, should be replaced by usage-based fees. Besides, the future Internet will carry heterogeneous flows such as video, voice, email, web, file transfers and remote login among others. Each of these applications requires a different level of QoS: for example, video needs very small delays and packet losses, voice requires small delays but can afford some packet losses, email can afford delay (within a given bound) while file transfer needs a good average throughput and remote login requires small round-trip times. Some pricing incentives should exist so that each user does not always choose the best QoS for her application and so that the final result is a fair utilization of the bandwidth. On the other hand, we need to be aware of the trade-off between engineering efficiency and economic efficiency; for example, traffic measurements can help in improving the management of the network but is a costly option. These are some of the various aspects often present in the pricing problems we address in our work. More recently, we have switched to the more general field of network economics, dealing with the economic behavior of users, service providers and content providers, as well as their relations.

DYOGENE Project-Team

3. Research Program

3.1. Network calculus

Network calculus [64] is a theory for obtaining deterministic upper bounds in networks that has been developed by R. Cruz [53], [54]. From the modelling point of view, it is an algebra for computing and propagating constraints given in terms of envelopes. A flow is represented by its cumulative function $R(t)$ (that is, the amount of data sent by the flow up to time t). A constraint on a flow is expressed by an arrival curve $\alpha(t)$ that gives an upper bound for the amount of data that can be sent during any interval of length t. Flows cross service elements that offer guarantees on the service. A constraint on a service is a service curve $\beta(t)$ that is used to compute the amount of data that can be served during an interval of length t. It is also possible to define in the same way minimal arrival curves and maximum service curves. Then such constraints envelop the processes and the services. Network calculus enables the following operations:
• computing the exact output cumulative function or at least bounding functions;
• computing output constraints for a flow (like an output arrival curve);
• computing the remaining service curve (that is, the service that of not used by the flows crossing a server);
• composing several servers in tandem;
• giving upper bounds on the worst-case delay and backlog (bounds are tight for a single server or a single flow).
The operations used for this are an adaptation of filtering theory to $(\min, +)$: $(\min, +)$ convolution and deconvolution, sub-additive closure.

We investigate the complexity of computing exact worst-case performance bounds in network calculus and to develop algorithms that present a good trade off between algorithmic efficiency and accuracy of the bounds.

3.2. Perfect Simulation

Simulation approaches can be used to efficiently estimate the stationary behavior of Markov chains by providing independent samples distributed according to their stationary distribution, even when it is impossible to compute this distribution numerically.

The classical Markov Chain Monte Carlo simulation techniques suffer from two main problems:
• The convergence to the stationary distribution can be very slow, and it is in general difficult to estimate;
• Even if one has an effective convergence criterion, the sample obtained after any finite number of iterations is biased.

To overcome these issues, Propp and Wilson [66] have introduced a perfect sampling algorithm (PSA) that has later been extended and applied in various contexts, including statistical physics [58], stochastic geometry [62], theoretical computer science [51], and communications networks [49], [57] (see also the annotated bibliography by Wilson [71]).

Perfect sampling uses coupling arguments to give an unbiased sample from the stationary distribution of an ergodic Markov chain on a finite state space $\mathcal{X}$. Assume the chain is given by an update function Φ and an i.i.d. sequence of innovations $(U_n)_{n\in\mathbb{Z}}$, so that

$$X_{n+1} = \Phi(X_n, U_{n+1}). \tag{1}$$

The algorithm is based on a backward coupling scheme: it computes the trajectories from all $x \in \mathcal{X}$ at some time in the past $t = -T$ until time $t = 0$, using the same innovations. If the final state is the same for all trajectories (i.e. $|\{\Phi(x, U_{-T+1}, ..., U_0) : x \in \mathcal{X}\}| = 1$, where $\Phi(x, U_{-T+1}, ..., U_0) := \Phi(\Phi(x, U_{-T+1}), U_{-T+2}, ..., U_0)$ is defined by induction on T), then we say that the chain has globally coupled and the final state has the stationary distribution of the Markov chain. Otherwise, the simulations are started further in the past.

Any ergodic Markov chain on a finite state space has a representation of type (1) that couples in finite time with probability 1, so Propp and Wilson's PSA gives a “perfect” algorithm in the sense that it provides a *unbiased* sample in *finite time*. Furthermore, the stopping criterion is given by the coupling from the past scheme, and knowing the explicit bounds on the coupling time is not needed for the validity of the algorithm.

However, from the computational side, PSA is efficient only under some monotonicity assumptions that allow reducing the number of trajectories considered in the coupling from the past procedure only to extremal initial conditions. Our goal is to propose new algorithms solving this issue by exploiting semantic and geometric properties of the event space and the state space.

3.3. Stochastic Geometry

Stochastic geometry [69] is a rich branch of applied probability which allows one to quantify random phenomena on the plane or in higher dimension. It is intrinsically related to the theory of point processes. Initially its development was stimulated by applications to biology, astronomy and material sciences. Nowadays it is also widely used in image analysis. It provides a way of estimating and computing “spatial averages”. A typical example, with obvious communication implications, is the so called Boolean model, which is defined as the union of discs with random radii (communication ranges) centered at the points of a Poisson point process (user locations) of the Euclidean plane (e.g., a city). A first typical question is that of the prediction of the fraction of the plane which is covered by this union (statistics of coverage). A second one is whether this union has an infinite component or not (connectivity). Further classical models include shot noise processes and random tessellations. Our research consists of analyzing these models with the aim of better understanding wireless communication networks in order to predict and control various network performance metrics. The models require using techniques from stochastic geometry and related fields including point processes, spatial statistics, geometric probability, percolation theory.

3.4. Information Theory

Classical models of stochastic geometry (SG) are not sufficient for analyzing wireless networks as they ignore the specific nature of radio channels.

Consider a wireless communication network made of a collection of nodes which in turn can be transmitters or receivers. At a given time, some subset of this collection of nodes simultaneously transmit, each toward its own receiver. Each transmitter–receiver pair in this snapshot requires its own wireless link. For each such wireless link, the power of the signal received from the link transmitter is jammed by the powers of the signals received from the other transmitters. Even in the simplest model where the power radiated from a point decays in some isotropic way with Euclidean distance, the geometry of the location of nodes plays a key role within this setting since it determines the signal to interference and noise ratio (SINR) at the receiver of each such link and hence the possibility of establishing simultaneously this collection of links at a given bit rate, as shown by information theory (IT). In this definition, the interference seen by some receiver is the sum of the powers of the signals received from all transmitters excepting its own. The SINR field, which is of an essentially geometric nature, hence determines the connectivity and the capacity of the network in a broad sense. The essential point here is that the characteristics and even the feasibilities of the radio links that are simultaneously active are strongly interdependent and determined by the geometry. Our work is centered on the development of an IT-aware stochastic geometry addressing this interdependence.

3.5. The cavity method for network algorithms

The cavity method combined with geometric networks concepts has recently led to spectacular progresses in digital communications through error-correcting codes. More than fifty years after Shannon's theorems, some coding schemes like turbo codes and low-density parity-check codes (LDPC) now approach the limits predicted by information theory. One of the main ingredients of these schemes is message-passing decoding strategies originally conceived by Gallager, which can be seen as direct applications of the cavity method on a random bipartite graph (with two types of nodes representing information symbols and parity check symbols, see [67]).

Modern coding theory is only one example of application of the cavity method. The concepts and techniques developed for its understanding have applications in theoretical computer science and a rich class of *complex systems*, in the field of networking, economics and social sciences. The cavity method can be used both for the analysis of randomized algorithms and for the study of random ensembles of computational problems representative real-world situations. In order to analyze the performance of algorithms, one generally defines a family of instances and endows it with a probability measure, in the same way as one defines a family of samples in the case of spin glasses or LDPC codes. The discovery that the hardest-to-solve instances, with all existing algorithms, lie close to a *phase transition* boundary has spurred a lot of interest. Theoretical physicists suggest that the reason is a structural one, namely a change in the geometry of the set of solutions related to the *replica symmetry breaking* in the cavity method. Phase transitions, which lie at the core of statistical physics, also play a key role in computer science [68], signal processing [56] and social sciences [61]. Their analysis is a major challenge, that may have a strong impact on the design of related algorithms.

We develop mathematical tools in the theory of discrete probabilities and theoretical computer science in order to contribute to a rigorous formalization of the cavity method, with applications to network algorithms, statistical inference, and at the interface between computer science and economics (EconCS).

3.6. Statistical learning

Sparse graph structures are useful in a number of information processing tasks where the computational problem can be described as follows: infer the values of a large collection of random variables, given a set of constraints or observations, that induce relations among them. Similar design ideas have been proposed in sensing and signal processing and have applications in coding [52], network measurements, group testing or multi-user detection. While the computational problem is generally hard, sparse graphical structures lead to low-complexity algorithms that are very effective in practice. We develop tools in order to contribute to a precise analysis of these algorithms and of their gap to optimal inference which remains a largely open problem.

A second line of activities concerns the design of protocols and algorithms enabling a transmitter to learn its environment (the statistical properties of the channel quality to the corresponding receiver, as well as their interfering neighbouring transmitters) so as to optimise their transmission strategies and to fairly and efficiently share radio resources. This second objective calls for the development and use of machine learning techniques (e.g. bandit optimisation).

FUN Project-Team

3. Research Program

3.1. Introduction

The research area of FUN research group is represented in Figure 1 . FUN research group will address every item of Figure 1 starting from the highest level of the figure, *i.e.* in area of homogeneous FUNs to the lowest one. Going down brings more applications and more issues to solve. Results achieved in the upper levels can be re-used in the lower ones. Current networks encountered nowadays are the ones at the higher level, without any interaction between them. In addition, solutions provided for such networks are rarely directly applicable in realistic networks because of the impact of the wireless medium.

FUN research group intends to fill the scientific gap and extend research performed in the area of wireless sensor and actor networks and RFID systems in two directions that are complementary and should be performed in parallel:

- **From theory to experimentation and reciprocally** On one hand, FUN research group intends to investigate new self-organization techniques for these future networks that take into account realistic parameters, emphasizing experimentation and considering mobility.
- **Towards heterogeneous FUNs** On the other hand, FUN research group intends to investigate techniques to allow heterogeneous FUNs to work together in a transparent way for the user. Indeed, new applications integrating several of these components are very much in demand (i.e. smart building) and thus these different technologies need to cooperate.

3.2. From theory to experimentation and reciprocally

Nowadays, even if some powerful and efficient propositions arise in the literature for each of these networks, very few are validated by experimentations. And even when this is the case, no lesson is learnt from it to improve the algorithms. FUN research group needs to study the limits of current assumptions in realistic and mobile environments.

Solutions provided by the FUN research group will mainly be algorithmic. These solutions will first be studied theoretically, principally by using stochastic geometry (like in [57]) or self-stabilization [59] tools in order to derive algorithm behavior in ideal environment. Theory is not an end in itself but only a tool to help in the characterization of the solution in the ideal world. For instance, stochastic geometry will allow quantifying changes in neighborhood or number of hops in a routing path. Self-stabilization will allow measuring stabilization times.

Those same solutions will then be confronted to realistic environments and their 'real' behavior will be analyzed and compared to the expected ones. Comparing theory, simulation and experimentation will allow will allow the influence of a realistic environment be better measured. From this and from the analysis of the information really available for nodes, FUN research group will investigate some means either to counterbalance these effects or to take advantage of them. New solutions provided by the FUN research group will take into consideration the vagaries of a realistic wireless environment and the node mobility. New protocols will take as inputs environmental data (as signal strength or node velocity/position, etc) and node characteristics (the node may have the ability to move in a controlled way) when available. FUN research group will thus adopt a **cross-layered** approach between hardware, physical environment, application requirements, self-organizing and routing techniques. For instance, FUN research group will study how the controlled node mobility can be exploited to enhance the network performance at lowest cost.

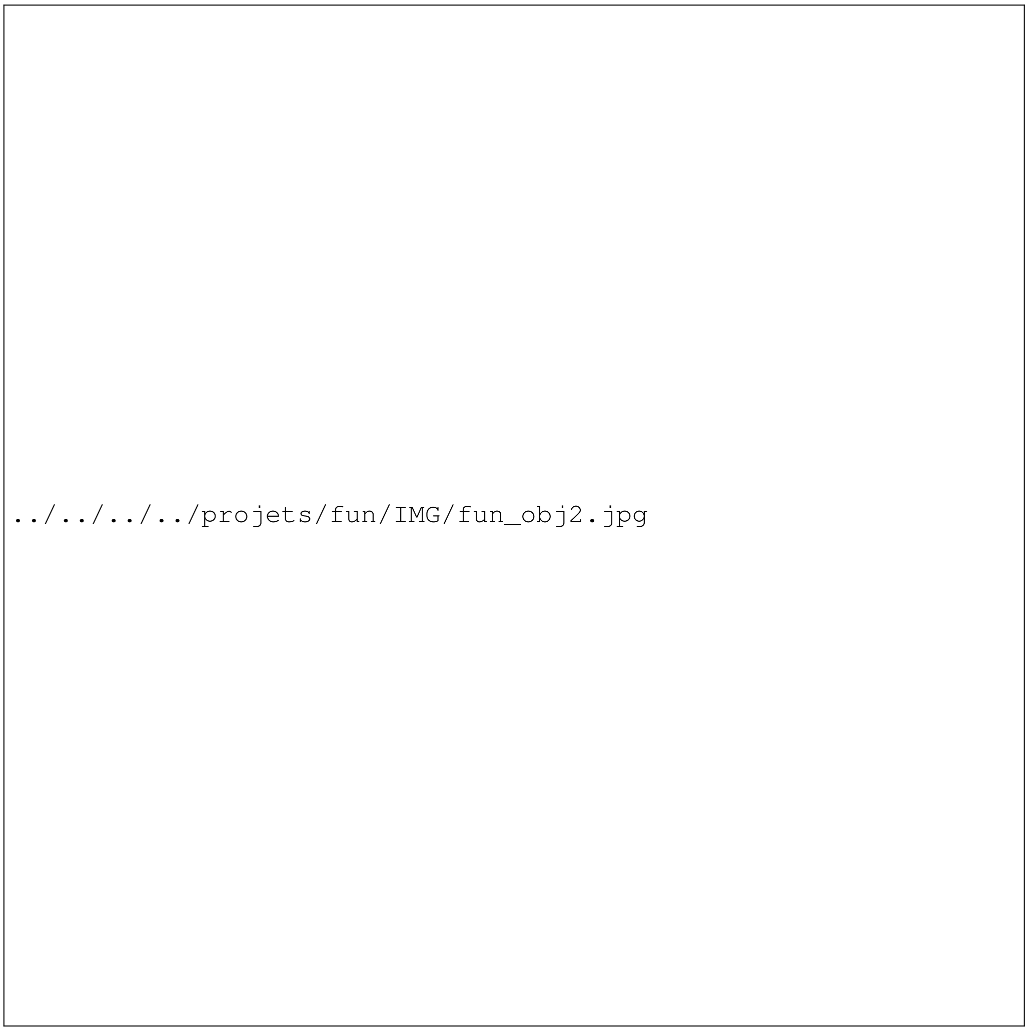

Figure 1. Panorama of FUN.

Solutions will follow the building process presented by Figure 2 . Propositions will be analyzed not only theoretically and by simulation but also by experimentation to observe the impact of the realistic medium on the behavior of the algorithms. These observations should lead to the derivation of cross-layered models. Experimentation feedbacks will be re-injected in solution design in order to propose algorithms that best fit the environment, and so on till getting satisfactory behavior in both small and large scale environments. All this should be done in such a way that the resulting propositions fit the hardware characteristics (low memory, CPU and energy capacity) and easy to deploy to allow their use by non experts. Since solutions should take into account application requirements as well as hardware characteristics and environment, solutions should be generic enough and then able to self-configure to adapt their environment settings.

In order to achieve this experimental environments, the FUN research group will maintain its strong activity on platform deployment such as SensLAB [63], FIT and Aspire [53]. Next steps will be to experiment not only on testbeds but also on real use cases. These latter will be given through different collaborations.

../../../../projets/fun/IMG/methodology.png

Figure 2. Methodology applied in the FUN research group.

FUN research group will investigate self-organizing techniques for FUNs by providing cross-layered solutions that integrate in their design the adaptability to the realistic environment features. Every solution will be validated with regards to specific application requirements and in realistic environments.

Facing the medium instability. The behavior of wireless propagation is very depending of the surrounding environment (in-door vs outdoor, night vs day, etc) and is very instable. Many experiments in different environment settings should be conducted. Experiment platforms such as SensLAB, FIT, our wifiBot as robots and actuators and our RFID devices will be used offering ways to experiment easily and quickly in different environments but might not be sufficient to experiment every environment.

Adaptability and flexibility. Since from one application to another one, requirements and environments are different, solutions provided by FUN research group should be **generic** enough and **self-adapt** to their environment. Algorithm design and validation should also take into account the targeted applications brought for instance by our industrial partners like Etineo. All solution designs should keep in mind the devices constrained capacities. Solutions should consume low resources in terms of memory, processor and energy to provide better performances and scale. All should be self-adaptive.

FUN research group will try to take advantage of some observed features that could first be seen as drawbacks. For instance, the broadcast nature of wireless networks is first an inconvenient since the use of a link between two nodes inhibits every other communication in the same transmission area. But algorithms should exploit that feature to derive new behaviors and a node blocked by another transmission should overhear it to get more information and maybe to limit the overall information to store in the network or overhead communication.

3.3. Towards unified heterogeneous FUNs

The second main direction to be followed by the FUN research group is to merge networks from the upper layer in Fig. 1 into networks from the lowest level. Indeed, nowadays, these networks are still considered as separated issues. But considering mixed networks bring new opportunities. Indeed, robots can deploy, replace, compensate sensor nodes. They also can collect periodically their data, which avoids some long and multi-hop communications between sensor nodes and thus preserving their resources. Robots can also perform many additional tasks to enhance network performance like positioning themselves on strategic points to ensure area coverage or reduce routing path lengths. Similarly, coupling sensors and RFID tags also bring new opportunities that are more and more in-demand from the industrial side. Indeed, an RFID reader may be a sensor in a wireless sensor network and data hold by RFID tags and collected by readers might need to be reported to a sink. This will allow new applications and possibilities such as the localization of a tagged object in an environment be covered by sensors.

When at last all components are gathered, this leads us to a new era in which every object is autonomous. Let's consider for instance a smart home equipped with sensors and RFID reader. An event triggered by a sensor (*i.e.* an increase of the temperature) or a RFID reader (*i.e.* detection of a tag hold by a person) will trigger actions from actuators (*i.e.* lowering of stores, door opening). Possibilities are huge. But with all these new opportunities come new technological issues with other constraints. Every entity is considered as an object possibly mobile which should be dynamically identified and controlled. To support this dynamics, protocols should be localized and distributed. Model derived from experiment observations should be unified to fit all these classes of devices.

FUN research group will investigate new protocols and communication paradigms that allow the technologies to be transparently merged. Objects and events might interconnect while respecting on-going standards and building an autonomic and smart network while being compliant with hardware resources and environment.

Technologies such as wireless sensors, wireless robots/actuators and RFID tags/ readers, although presenting many common points are still part of different disciplines that have evolved in parallel ways. Every branch is at different maturity levels and has developed its own standards. Nevertheless, making all these devices part of a single unified network leverages technological issues (partly addressed in the former objective) but also regarding to on-going standards and data formatting. FUN research group will have to study current standards of every area in order to propose compliant solutions. Such works have been initiated in the POPS research group in the framework of the FP7 ASPIRE project. Members of FUN research group intend to continue and enlarge these works.

Todays' EPCGlobal compliant RFID readers must comply to some rules and be configurable through an ALE (Application Level Event) [51]. While a fixed and connected RFID reader is easily configurable, configuring remotely a mobile RFID reader might be very difficult since it implies to first locate it and then send configuration data through a wireless dynamic network. FUN research group will investigate some tools that make the configuration easy and transparent for the user. This remote configuration of mobile readers through the network should consider application requirements and network and reader characteristics to choose the best trade-off relative to the software part embedded in the reader. The biggest part embedded, the lowest bandwidth overhead (data can be filtered and aggregated in the reader) and the greater mobility (readers are still fully operational even when disconnected) but the more difficult to set up and the more powerful readers. All these aspects will be studied within the FUN research group.

GANG Project-Team

3. Research Program

3.1. Research Program

Taking into account the scientific achievements of the last years, and the short presentation section above, GANG is currently focusing on the following objectives:

- Graphs algorithms
- Distributed Computing
- P2P-like Algorithms for Future Networks

3.1.1. Graph algorithms

3.1.1.1. Graph Decompositions

We study new decompositions schemes such as 2-join, skew partitions and others partition problems. These graph decompositions appeared in the structural graph theory and are the basis of some well-known theorems such as the Perfect Graph Theorem. For these decompositions there is a lack of efficient algorithms. We aim at designing algorithms working in $O(nm)$ since we think that this could be a lower bound for these decompositions.

3.1.1.2. Graph Search

We more deeply study multi-sweep graph searches. In this domain a graph search only yields a total ordering of the vertices which can be used by the subsequent graph searches. This technique can be used on huge graphs and do not need extra memory. We already have obtained preliminary results in this direction and many well-known graph algorithms can be put in this framework. The idea behind this approach is that each sweep discovers some structure of the graph. At the end of the process either we have found the underlying structure (for example an interval representation for an interval graph) or an approximation of it (for example in hard discrete optimization problems). Application to exact computations of centers in huge graphs, to underlied combinatorial optimization problems, but also to networks arising in Biology.

3.1.2. Distributed computing

The distributed community can be viewed as the union of two sub-communities. This is true even in our team. Even though they are not completely disjoint, they are disjoint enough not to leverage each other's results. At a high level, one is mostly interested in timing issues (clock drifts, link delays, crashes, etc.) while the other one is mostly interested in spatial issues (network structure, memory requirements, etc.). Indeed, one sub-community is mostly focusing on the combined impact of asynchronism and faults on distributed computation, while the other addresses the impact of network structural properties on distributed computation. Both communities address various forms of computational complexities, through the analysis of different concepts. This includes, e.g., failure detectors and wait-free hierarchy for the former community, and compact labeling schemes and computing with advice for the latter community. We have the ambitious project to achieve the reconciliation between the two communities by focusing on the same class of problems, the yes/no-problems, and establishing the scientific foundations for building up a consistent theory of computability and complexity for distributed computing. The main question addressed is therefore: is the absence of globally coherent computational complexity theories covering more than fragments of distributed computing, inherent to the field? One issue is obviously the types of problems located at the core of distributed computing. Tasks like consensus, leader election, and broadcasting are of very different nature. They are not *yes-no* problems, neither are they minimization problems. Coloring and Minimal Spanning Tree are optimization problems but we are often more interested in constructing an optimal solution than in verifying the correctness of a given solution. Still, it makes full sense to analyze the *yes-no* problems corresponding to checking the validity of the output of tasks. Another issue is the power of individual computation. The FLP impossibility result as well as Linial's lower bound hold independently from the individual computational power of the involved computing entities. For instance, the individual power of solving NP-hard problems in constant time would not help overcoming these limits which are inherent to the fact that computation is distributed. A third issue is the abundance of models for distributed computing frameworks, from shared memory to message passing, spanning all kinds of specific network structures (complete graphs, unit-disk graphs, etc.) and or timing constraints (from complete synchronism to full asynchronism). There are however models, typically the wait-free model and the LOCAL model, which, though they do not claim to reflect accurately real distributed computing systems, enable focusing on some core issues. Our research program is ongoing to carry many important notions of Distributed Computing into a *standard* computational complexity.

3.1.3. A Peer-to-Peer approach to future content Distribution

Unexpectedly, the field of P2P applications is still growing and challenging issues remain worth studying.

3.1.3.1. New network models

The new models that have been proposed to take into account the evolution of network architecture and usage indicate new opportunities for P2P, like the possibility to have superscalable systems whose performance increases with the popularity. This surprising property, if it can be enforced, will give P2P an additional asset compared to the current situation. However, this results are still at an early stage, and it is planned to continue the study from a theoretical point of view, but also with experimentations with emulation and/or simulation of future networks on large grids.

3.1.3.2. P2P storage

The challenges of a persistent and robust distributed storage with respect to failures are nowadays relatively well understood. However, the results about instant availability are still not completely understood: how to give guarantees, in a P2P system where peers are not online 100% of the time, that a content will be available when its owner asks for it? Can we propose some allocation policy that ensures maximal availability with only a partial knowledge of online patterns? We believe that these issues, halfway between failure tolerance and opportunistic networks, are still promising.

3.1.3.3. Caching allocation

Today, most of content distribution is ensured by so-called Content Distribution Networks (CDNs). It is expected that caching techniques will remain a hot topic in the years to come, for instance through the studies related to Content Centric Networking, which is inspired by P2P content distribution paradigms, like using so-called chunks as the basic data exchange unit. Many challenges in this field are related to dimensioning and caching strategies. In GANG, we aim at conducting a study centered on the trade-offs between storage and bandwidth usage. Note that many studies have been/are realized on this topic, mostly rely on operational research methodology and offer solutions that can sometimes be difficult to use in practice. GANG uses a different approach, based on alternate modeling assumptions inherited from our previous achievments on bandwidth dimensioning. The goal of this complementary approach is to provide simple dimensioning guidelines while giving approximated, yet meaningful, performance evaluation.

3.1.3.4. Long term perspective on P2P content distribution

The success of YouTube-like delivery platforms (YouTube, DailyMotion...) does not come only from their technical performances, but from the ergonomy: these platforms allow to launch a video directly from one's browser, without the usual burden that comes with traditional P2P applications (install a specific client, open incoming ports, find .torrent files . . .). It is therefore important to keep working on basic P2P research, especially as many challenges are still open (see above), and new opportunities are likely to rise. First, advances in other fields may make P2P more interesting than other solutions –again. For instance, CCN protocols are designed to facilitate data dissemination. One could hope they open the way to CCN-assisted P2P protocols, where both the issues of ergonomy and network burden would be taken care of by design. Unpredictable events, such as emerging/closing centralized filesharing services, can also change the power balance very fast with effects that are still hard to determine. For all these reasons, GANG aims at improving its expertise in the field of decentralized content distribution, even if it is quite difficult at the fast evolving current time to tell if that expertise should apply on traditional P2P, CCN, Cloud... architectures, or on any hybridation of these.

HIPERCOM2 Team

3. Research Program

3.1. Methodology of telecommunication algorithm evaluation

We develop our performance evaluation tools towards deterministic performance and probabilistic performance. Our tools range from mathematical analysis to simulation and real life experiment of telecommunication algorithms.

One cannot design good algorithms without good evaluation models. Hipercom project team has an historically strong experience in performance evaluation of telecommunication systems, notably when they have multiple access media. We consider two main methodologies:

- Deterministic performance analysis,
- Probabilistic performance analysis

In the deterministic analysis, the evaluation consists in identifying and quantifying the worst case scenario for an algorithm in a given context. For example to evaluate an end-to-end delay. Mathematically it consists into handling a (max,+) algebra. Since such algebra is not commutative, the complexity of the evaluation of an end-to-end delay frequently grows exponentially with the number of constraints. Therefore the main issue in the deterministic evaluation of performance is to find bounds easier to compute in order to have practical results in realistic situations.

In the probabilistic analysis of performance, one evaluate the behavior of an algorithm under a set of parameters that follows a stochastic model. For example traffic may be randomly generated, nodes may move randomly on a map. The pionneer works in this area come from Knuth (1973) who has systematized this branch. In the domain of telecommunication, the domain has started a significant rise with the appearance of the problematic of collision resolution in a multiple access medium. With the rise of wireless communication, new interesting problems have been investigated.

The analysis of algorithm can rely on analytical methodology which provides the better insight but is practical in very simplistic models. Simulation tools can be used to refine results in more complicated models. At the end of the line, we proceed with real life experiments. To simplify, experiments check the algorithms with 10 nodes in maximum, simulations with 100 nodes maximum, analytical tools with more 1,000 nodes, so that the full range of applicability of the algorithms is investigated.

3.2. Traffic and network architecture modeling

One needs good and realistic models of communication scenarios in order to provide pertinent performance evaluation of protocols. The models must assess the following key points:

- The architecture and topology: the way the nodes are structured within the network
- The mobility: the way the nodes move
- The dynamics: the way the nodes change status
- The traffic: the way the nodes communicate

For the architecture there are several scales. At the internet scale it is important to identify the patterns which dictate the node arrangement. For example the internet topology involves many power law distribution in node degree, link capacities, round trip delays. These parameters have a strong impact in the performance of the global network. At a smaller scale there is also the question how the nodes are connected in a wireless network. There is a significant difference between indoor and outdoor networks. The two kinds of networks differ on wave propagation. In indoor networks, the obstacles such as walls, furniture, etc, are the main source of signal attenuations. In outdoor networks the main source of signal attenuation is the distance to the emitter. This lead to very different models which vary between the random graph model for indoor networks to the unit graph model for outdoor networks.

The mobility model is very important for wireless network. The way nodes move may impact the performance of the network. For example it determines when the network splits in distinct connected components or when these components merge. With random graph models, the mobility model can be limited to the definition of a link status holding time. With unit disk model the mobility model will be defined according to random speed and direction during random times or random distances. There are some minor complications on the border of the map.

The node dynamic addresses the elements that change inside the node. For example its autonomy, its bandwidth requirement, the status of server, client, etc. Pair to pair networks involve a large class of users who frequently change status. In a mobile ad hoc network, nodes may change status just by entering or leaving the coverage area.

The traffic model is very most important. There are plenty of literature about trafic models which arose when Poisson models was shown not to be accurate for real traffics, on web or on local area networks. Natural traffic shows long range dependencies that do not exist in Poisson traffic. There are still strong issues about the origin of this long range dependencies which are debated, however they have a great impact on network performance since congestions are more frequent. The origin are either from the distribution of file sizes exchanged over the net, or from the protocols used to exchange them. One way to model the various size is to consider on/off sources. Every time a node is on it transfers a file of various size. The TCP protocol has also an impact since it keeps a memory on the network traffic. One way to describe it is to use an on/off model (a source sending packets in transmission windows) and to look at the superposition of these on/off sources.

3.3. Algorithm design, evaluation and implementation

The conception of algorithms is an important focus of the team. We specify algorithms in the perspective of achieving the best performance for communication. We also strive to embed those algorithms in protocols that involve the most legacy from existing technologies (Operating systems, internet, Wifi). Our aim with this respect is to allow code implementations for real life experiment or embedded simulation with existing network simulators. The algorithm specified by the project ranges from multiple access schemes, wireless ad hoc routing, to deployment of wireless sensor nodes as well as joint time slot and channel assignment in wireless networks. In any of these cases the design emphasize the notions of performance, robustness and flexibility. For example, a flooding technique in mobile ad hoc network should save bandwidth but should not stick too much close to optimal in order to be more reactive to frequent topology changes. Some telecommunication problems have NP hard optimal solution, and an implementable algorithm should be portable on very low power processing unit (e.g. sensors). Compromise have to be found and quantified with respect to nearly optimal solution.

3.4. Simulation of network algorithms and protcols

the perforamnce of algorithms and procols designed by the team have to be evaluated in various conditions: various configurations and various scenarii. The team uses different simulation tools. Historically, the first one was NS2 and some deployment algorithms are developed with NS2, taking advantage of its library and our previous works. We are now contributing to the development of NS3, enriching it with new modules (e.g. wireless medium access). For rapid simulation results and to validate design choices, we resort to Java home-made simulation tools (e.g. joint time slot and channel allocation).

MADYNES Project-Team

3. Research Program

3.1. Evolutionary needs in network and service management

The foundation of the MADYNES research activity is the ever increasing need for automated monitoring and control within networked environments. This need is mainly due to the increasing dependency of both people and goods towards communication infrastructures as well as the growing demand towards services of higher quality. Because of its strategic importance and crucial requirements for interoperability, the management models were constructed in the context of strong standardization activities by many different organizations over the last 15 years. This has led to the design of most of the paradigms used in today's deployed approaches. These paradigms are the Manager/Agent interaction model, the Information Model paradigm and its container, together with a naming infrastructure called the Management Information Base. In addition to this structure, five functional areas known under Fault, Configuration, Accounting, Performance and Security are associated to these standards.

While these models were well suited for the specific application domains for which they were designed (telecommunication networks or dedicated protocol stacks), they all show the same limits. Especially they are unable:

1. to deal with any form of dynamicity in the managed environment,
2. to master the complexity, the operating mode and the heterogeneity of the emerging services,
3. to scale to new networks and service environments.

These three limits are observed in all five functional areas of the management domain (fault, configuration, accounting, performance and security) and represent the major challenges when it comes to enable effective automated management and control of devices, networks and services in the next decade.

MADYNES addresses these challenges by focusing on the design of management models that rely on inherently dynamic and evolving environments. The project is centered around two core activities. These activities are, as mentioned in the previous section, the design of an autonomous management framework and its application to three of the standard functional areas namely security, configuration and performance.

3.2. Autonomous management

3.2.1. Models and methods for a self-management plane

Self organization and automation are fundamental requirements within the management plane in today's dynamic environments. It is necessary to automate the management processes and enable management frameworks to operate in time sensitive evolving networks and service environments. The automation of the organization of devices, software components, networks and services is investigated in many research projects and has already led to several solution proposals. While these proposals are successful at several layers, like IP auto-configuration or service discovery and binding facilities, they did not enhance the management plane at all. For example, while self-configuration of IP devices is commonplace, no solution exists that provides strong support to the management plane to configure itself (e.g. finding the manager to which an agent has to send traps or organizing the access control based on locality or any other context information). So, this area represents a major challenge in extending current management approaches so that they become self-organized.

Our approach is bottom-up and consists in identifying those parameters and framework elements (manager data, information model sharing, agent parameters, protocol settings, ...) that need dynamic configuration and self-organization (like the address of a trap sink). For these parameters and their instantiation in various management frameworks (SNMP, Netconf, WBEM, ...), we investigate and elaborate novel approaches enabling fully automated setup and operation in the management plane.

3.2.2. Design and evaluation of P2P-based management architectures

Over the last years, several models have emerged and gained wide acceptance in the networking and service world. Among them, the overlay networks together with the P2P paradigms appear to be very promising. Since they rely mainly on fully decentralized models, they offer excellent fault tolerance and have a real potential to achieve high scalability. Mainly deployed in the content delivery and the cooperation and distributed computation disciplines, they seem to offer all features required by a management framework that needs to operate in a dynamic world. This potential however needs an in depth investigation because these models have also many characteristics that are unusual in management (e.g. a fast and uncontrolled evolution of the topology or the existence of a distributed trust relationship framework rather than a standard centralized security framework).

Our approach envisions how a complete redesign of a management framework is done given the characteristics of the underlying P2P and overlay services. Among the topics of interest we study the concept of management information and operations routing within a management overlay as well as the distribution of management functions in a multi-manager/agent P2P environment. The functional areas targeted in our approach by the P2P model are network and service configuration and distributed monitoring. The models are to be evaluated against highly dynamic frameworks such as ad-hoc environments (network or application level) and mobile devices.

3.2.3. Integration of management information

Representation, specification and integration of management information models form a foundation for network and service management and remains an open research domain. The design and specification of new models is mainly driven by the appearance of new protocols, services and usage patterns. These need to be managed and exposed through well designed management information models. Integration activities are driven by the multiplication of various management approaches. To enable automated management, these approaches need to inter-operate which is not the case today.

The MADYNES approach to this problem of modeling and representation of management information aims at:

1. enabling application developers to establish their management interface in the same workspace, with the same notations and concepts as the ones used to develop their application,
2. fostering the use of standard models (at least the structure and semantics of well defined models),
3. designing a naming structure that allows the routing of management information in an overlay management plane, and
4. evaluating new approaches for management information integration especially based on management ontologies and semantic information models.

3.2.4. Modeling and benchmarking of dynamic networks

The impact of a management approach on the efficiency of the managed service is highly dependent on three factors:

- the distribution of the considered service and their associated management tasks,
- the management patterns used (e.g. monitoring frequency, granularity of the management information considered),
- the cost in terms of resources these considered functions have on the managed element (e.g. method call overhead, management memory footprint).

MADYNES addresses this problem from multiple viewpoints: communication patterns, processing and memory resources consumption. Our goal is to provide management patterns combining optimized management technologies so as to optimize the resources consumed by the management activity imposed by the operating environment while ensuring its efficiency in large dynamic networks.

3.3. Functional areas

3.3.1. Security management

Securing the management plane is vital. While several proposals are already integrated in the existing management frameworks, they are rarely used. This is due to the fact that these approaches are completely detached from the enterprise security framework. As a consequence, the management framework is "managed" separately with different models; this represents a huge overhead. Moreover the current approaches to security in the management plane are not inter-operable at all, multiplying the operational costs in a heterogeneous management framework.

The primary goal of the research in this activity is the design and the validation of a security framework for the management plane that will be open and capable to integrate the security services provided in today's management architectures. Management security interoperability is of major importance in this activity.

Our activity in this area aims at designing a generic security model in the context of multi-party / multi-technology management interactions. Therefore, we develop research on the following directions:

1. Abstraction of the various access control mechanisms that exist in today's management frameworks. We are particularly interested in extending these models so that they support event-driven management, which is not the case for most of them today.
2. Extension of policy and trust models to ease and to ensure coordination among managers towards one agent or a subset of the management tree. Provisional policies are of great interest to us in this context.
3. Evaluation of the adequacy of key distribution architectures to the needs of the management plane as well as selecting reputation models to be used in the management of highly dynamic environments (e.g. multicast groups, ad-hoc networks).

A strong requirement towards the future generic model is that it needs to be instantiated (with potential restrictions) into standard management platforms like SNMP, WBEM or Netconf and to allow interoperability in environments where these approaches coexist and even cooperate. A typical example of this is the security of an integration agent which is located in two management worlds.

Since 2006 we have also started an activity on security assessment. The objective is to investigate new methods and models for validating the security of large scale dynamic networks and services. The first targeted service is VoIP.

3.3.2. Configuration: automation of service configuration and provisioning

Configuration covers many processes which are all important to enable dynamic networks. Within our research activity, we focus on the operation of tuning the parameters of a service in an automated way. This is done together with the activation topics of configuration management and the monitoring information collected from the underlying infrastructure. Some approaches exist today to automate part of the configuration process (download of a configuration file at boot time within a router, on demand code deployment in service platforms). While these approaches are interesting they all suffer from the same limits, namely:

1. they rely on specific service life cycle models,
2. they use proprietary interfaces and protocols.

These two basic limits have high impacts on service dynamics in a heterogeneous environment.

We follow two research directions in the topic of configuration management. The first one aims at establishing an abstract life-cycle model for either a service, a device or a network configuration and to associate with this model a generic command and programming interface. This is done in a way similar to what is proposed in the area of call control in initiatives such as Parlay or OSA.

In addition to the investigation of the life-cycle model, we work on technology support for distributing and exchanging configuration management information. Especially, we investigate policy-driven approaches for representing configurations and constraints while we study XML-based protocols for coordinating distribution and synchronization. Off and online validation of configuration data is also part of this effort.

3.3.3. Performance and availability monitoring

Performance management is one of the most important and deployed management function. It is crucial for any service which is bound to an agreement about the expected delivery level. Performance management needs models, metrics, associated instrumentation, data collection and aggregation infrastructures and advanced data analysis algorithms.

Today, a programmable approach for end-to-end service performance measurement in a client server environment exists. This approach, called Application Response Measurement (ARM) defines a model including an abstract definition of a unit of work and related performance records; it offers an API to application developers which allows easy integration of measurement within their distributed application. While this approach is interesting, it is only a first step toward the automation of performance management.

We are investigating two specific aspects. First we are working on the coupling and possible automation of performance measurement models with the upper service level agreement and specification levels. Second we are working on the mapping of these high level requirements to the lower level of instrumentation and actual data collection processes available in the network. More specifically we are interested in providing automated mapping of service level parameters to monitoring and measurement capabilities. We also envision automated deployment and/or activation of performance measurement sensors based on the mapped parameters. This activity also incorporates self-instrumentation (and when possible on the fly instrumentation) of software components for performance monitoring purpose.

MAESTRO Project-Team

3. Research Program

3.1. Research Directions

MAESTRO follows six main research directions: network science, wireless networks, network engineering games, green networking and smart grids, content-oriented systems, and advances in methodological tools. These directions are very connected: network engineering games find applications in many networking fields, and methodological advances are typically motivated by applications.

3.1.1. Network Science

MAESTRO contributes to this new fast growing research subject. “Network Science” or “Complex Network Analysis” aims at understanding the structural properties and the dynamics of a variety of large-scale networks in telecommunications (e.g. the graph of autonomous systems, the Web graph), social science (e.g. community of interest, advertisement, reputation, recommendation systems), bibliometrics (e.g. citations, co-authors), biology (e.g. spread of an epidemic, protein-protein interactions), and physics. It has been observed that the complex networks encountered in these areas share common properties such as power law degree distribution, small average distances, community structure, etc. It also appears that many general questions/applications (e.g. community detection, epidemic spreading, search, anomaly detection) are common in various disciplines which study networks. In particular, we aim at understanding the evolution of complex networks with the help of game theoretical tools in connection with Network Engineering Games, as described below. We design efficient tools for measuring specific properties of large scale complex networks and their dynamics. More specifically, we work on the problem of distributed optimization in large networks where nodes cooperatively solve an optimization problem relying only on local information exchange.

3.1.2. Wireless Networks

The amazing technological advances in wireless devices has led networks to become heterogeneous and very complex. Many research groups worldwide investigate performance evaluation of wireless technologies. MAESTRO’s specificity relies on the use of a large variety of analytic tools from applied probability, control theory and distributed optimization to study and improve wireless network functionalities.

3.1.3. Network Engineering Games

The foundations of *Network Engineering Games* are currently being laid. These are games arising in telecommunications engineering at all the networking layers. This includes considerations from information and communications theory for dealing with the physical and link layers, along with cross layer approaches. MAESTRO’s focus is on three areas: *routing games*, *evolutionary games* and *epidemic games*. In routing games we progress on the theory for costs that are not additive over links (such as packet losses or call blocking probabilities). We pursue our research in the stochastic extension of evolutionary game theory, namely the “anonymous sequential games” in which we study the total expected costs and the average cost. Within epidemic games we study epidemics that compete against each other. We apply this to social networks, considering in particular the coupling between various social networks (e.g. propagation strategies that combine Twitter, FaceBook and other social networks).

3.1.4. Green Networking and Smart Grids

The ICT (Information and Communications Technology) sector is becoming one of the main energy consumers worldwide. There is awareness that networks should have a reduced environmental footprint. Our objective is to have a systematically “green” approach when solving optimization problems. The energy cost and the environmental impact should be considered in optimization functions along with traditional performance metrics such as throughput, fairness or delay. We aim at contributing to the design and the analysis of future green networks, in particular those using renewable energy.

Researchers envision that future electricity distribution network will be “smart”, with a large number of small generators (due to an extensive use of renewable energies) and of consumer devices able to adapt their energy needs to a time-varying offer. Generators and devices will be able to locally communicate through the electrical grid itself (or more traditional communication networks), in order to optimize production, transport and use of the energy. This is definitely a new application scenario for MAESTRO, to which we hope to be able to contribute with our expertise on analytic models and performance evaluation.

3.1.5. Content-Oriented Systems

We generally study problems related with the placement of data in communication networks. We are particularly interested in In-network caching, a widely adopted technique to provide an efficient access to data or resources on a world-wide deployed system while ensuring scalability and availability. For instance, caches are integral components of the Domain Name System, the World Wide Web, Content Distribution Networks, or the recently proposed Information-Centric Network (ICN) architectures. We analyze network of caches, study their optimal placement in the network and optimize data placement in caches/servers.

3.1.6. Advances in Methodological Tools

MAESTRO has a methodological activity that aims at advancing the state of the art in the methodological tools used for the general performance evaluation and control of systems. We contribute to such fields as perturbation analysis, Markov processes, queueing theory, control theory and game theory. Another objective is to enhance our activity on general-purpose modeling algorithms and software for controlled and uncontrolled stochastic systems.

3.2. Scientific Foundations

The main mathematical tools and formalisms used in MAESTRO include:

- theory of stochastic processes: Markov process, renewal process, branching process, point process, Palm measure, large deviations, mean-field approximation, fluid approximation;
- theory of dynamical discrete-event systems: queues, pathwise and stochastic comparisons, random matrix theory;
- theory of control and scheduling: dynamic programming, Markov decision process, game theory, deterministic and stochastic scheduling;
- theory of singular perturbations.

RAP Project-Team

3. Research Program

3.1. Design and Analysis of Algorithms

Data Structures, Stochastic Algorithms

The general goal of the research in this domain is of designing algorithms to analyze and control the traffic of communication networks. The team is currently involved in the design of algorithms to allocate bandwidth in optical networks and also to allocate resources in content-centric networks. See the corresponding sections below.

The team also pursues analysis of algorithms and data structures in the spirit of the former Algorithms team. The team is especially interested in the ubiquitous divide-and-conquer paradigm and its applications to the design of search trees, and stable collision resolution protocols.

3.2. Scaling of Markov Processes

The growing complexity of communication networks makes it more difficult to apply classical mathematical methods. For a one/two-dimensional Markov process describing the evolution of some network, it is sometimes possible to write down the equilibrium equations and to solve them. The key idea to overcome these difficulties is to consider the system in limit regimes. This list of possible renormalization procedures is, of course, not exhaustive. The advantages of these methods lie in their flexibility to various situations and to the interesting theoretical problems they raised.

A fluid limit scaling is a particularly important means to scale a Markov process. It is related to the first order behavior of the process and, roughly speaking, amounts to a functional law of large numbers for the system considered.

A fluid limit keeps the main characteristics of the initial stochastic process while some second order stochastic fluctuations disappear. In “good” cases, a fluid limit is a deterministic function, obtained as the solution of some ordinary differential equation. As can be expected, the general situation is somewhat more complicated. These ideas of rescaling stochastic processes have emerged recently in the analysis of stochastic networks, to study their ergodicity properties in particular.

3.3. Structure of random networks

This line of research aims at understanding the global structure of stochastic networks (connectivity, magnitude of distances, etc) via models of random graphs. It consists of two complementary foundational and applied aspects of connectivity.

RANDOM GRAPHS, STATISTICAL PHYSICS AND COMBINATORIAL OPTIMIZATION. The connectivity of usual models for networks based on random graphs models (Erdős–Rényi and random geometric graphs) may be tuned by adjusting the average degree. There is a *phase transition* as the average degree approaches one, a *giant* connected component containing a positive proportion of the nodes suddenly appears. The phase of practical interest is the *supercritical* one, when there is at least a giant component, while the theoretical interest lies at the *critical phase*, the break-point just before it appears.

At the critical point there is not yet a macroscopic component and the network consists of a large number of connected component at the mesoscopic scale. From a theoretical point of view, this phase is most interesting since the structure of the clusters there is expected (heuristically) to be *universal*. Understanding this phase and its universality is a great challenge that would impact the knowledge of phase transitions in all high-dimensional models of *statistical physics* and *combinatorial optimization*.

RANDOM GEOMETRIC GRAPHS AND WIRELESS NETWORKS. The level of connection of the network is of course crucial, but the *scalability* imposes that the underlying graph also be *sparse*: trade offs must be made, which required a fine evaluation of the costs/benefits. Various direct and indirect measures of connectivity are crucial to these choices: What is the size of the overwhelming connected component? When does complete connectivity occur? What is the order of magnitude of distances? Are paths to a target easy to find using only local information? Are there simple broadcasting algorithms? Can one put an end to viral infections? How much time for a random crawler to see most of the network?

NAVIGATION AND POINT LOCATION IN RANDOM MESHES. Other applications which are less directly related to networks include the design of improved navigation or point location algorithms in geometric meshes such as the Delaunay triangulation build from random point sets. There the graph model is essentially fixed, but the constraints it imposes raise a number of challenging problems. The aim is to prove performance guarantees for these algorithms which are used in most manipulations of the meshes.

SOCRATE Project-Team

3. Research Program

3.1. Research Axes

In order to keep young researchers in an environment close to their background, we have structured the team along the three research axes related to the three main scientific domains spanned by Socrate. However, we insist that a *major objective* of the Socrate team is to *motivate the collaborative research between these axes*, this point is specifically detailed in section 3.5 . The first one is entitled “Flexible Radio Front-End” and will study new radio front-end research challenges brought up by the arrival of MIMO technologies, and reconfigurable front-ends. The second one, entitled “Agile Radio Resource Sharing”, will study how to couple the self-adaptive and distributed signal processing algorithms to cope with the multi-scale dynamics found in cognitive radio systems. The last research axis, entitled “Software Radio Programming Models” is dedicated to embedded software issues related to programming the physical protocols layer on these software radio machines. Figure 4 illustrates the three regions of a transceiver corresponding to the three Socrate axes.

3.2. Flexible Radio Front-End

Participants: Guillaume Villemaud, Florin Hutu.

This axis mainly deals with the radio front-end of software radio terminals (right of Fig 4). In order to ensure a high flexibility in a global wireless network, each node is expected to offer as many degrees of freedom as possible. For instance, the choice of the most appropriate communication resource (frequency channel, spreading code, time slot,...), the interface standard or the type of antenna are possible degrees of freedom. The *multi-** paradigm denotes a highly flexible terminal composed of several antennas providing MIMO features to enhance the radio link quality, which is able to deal with several radio standards to offer interoperability and efficient relaying, and can provide multi-channel capability to optimize spectral reuse. On the other hand, increasing degrees of freedom can also increase the global energy consumption, therefore for energy-limited terminals a different approach has to be defined.

In this research axis, we expect to demonstrate optimization of flexible radio front-end by fine grain simulations, and also by the design of home made prototypes. Of course, studying all the components deeply would not be possible given the size of the team, we are currently not working in new technologies for DAC/ADC and power amplifiers which are currently studied by hardware oriented teams. The purpose of this axis is to build system level simulation taking into account the state of the art of each key component.

3.3. Agile Radio Resource Sharing

Participants: Jean-Marie Gorce, Claire Goursaud, Nikolai Lebedev.

The second research axis is dealing with the resource sharing problem between uncoordinated nodes but using the same (wide) frequency band. The agility represents the fact that the nodes may adapt their transmission protocol to the actual radio environment. Two features are fundamental to make the nodes agile : the first one is related to the signal processing capabilites of the software radio devices (middle circle in Fig 4), including modulation, coding, interference cancelling, sensing... The set of all available processing capabilites offers the degrees of freedom of the system. Note how this aspect relies on the two other research axes: radio front-end and radio programming.

But having processing capabilities is not enough for agility. The second feature for agility is the decision process, i.e. how a node can select its transmission mode. This decision process is complex because the appropriateness of a decision depends on the decisions taken by other nodes sharing the same radio environment. This problem needs distributed algorithms, which ensure stable and efficient solutions for a fair coexistence.

../../../../projets/socrate/IMG/radioBlockAxes.png

Figure 4. Center of interest for each of the three Socrate research axes with respect to a generic software radio terminal.

Beyond coexistence, the last decade saw a tremendous interest in cooperative techniques that let the nodes do more than coexisting. Of course, cooperation techniques at the networking or MAC layers for nodes implementing the same radio standard are well-known, especially for mobile ad-hoc networks, but cooperative techniques for SDR nodes at the PHY layer are still really challenging. The corresponding paradigm is the one of opportunistic cooperation, let us say *on-the-fly*, further implemented in a distributed manner.

We propose to structure our research into three directions. The two first directions are related to algorithmic developments, respectively for radio resource sharing and for cooperative techniques. The third direction takes another point of view and aims at evaluating theoretical bounds for different network scenarios using Network Information Theory.

3.4. Software Radio Programming Model

Participants: Tanguy Risset, Kevin Marquet, Guillaume Salagnac.

Finally the third research axis is concerned with software aspect of the software radio terminal (left of Fig 4). We have currently two actions in this axis, the first one concerns the programming issues in software defined radio devices, the second one focusses on low power devices: how can they be adapted to integrate some reconfigurability.

The expected contributions of Socrate in this research axis are :

- The design and implementation of a “middleware for SDR”, probably based on a Virtual Machine.
- Prototype implementations of novel software radio systems, using chips from Leti and/or Lyrtech software radio boards [1].
- Development of a *smart node*: a low-power Software-Defined Radio node adapted to WSN applications.
- Methodology clues and programming tools to program all these prototypes.

3.5. Inter-Axes collaboration

As mentioned earlier, innovative results will come from collaborations between these three axes. To highlight the fact that this team structure does not limit the ability of inter-axes collaborations between Socrate members, we list below the *on-going* research actions that *already* involve actors from two or more axes, this is also represented on Fig 5 .

- *Optimizing network capacity of very large scale networks.* 2 Phds started in October/November 2011 with Guillaume Villemaud (axis 1) and Claire Goursaud (axis 2).
- *SDR for sensor networks.* A PhD started in 2012 in collaboration with FT R&D, involving people from axis 3 (Guillaume Salagnac, Tanguy Risset) and axis 1 (Guillaume Villemaud).
- *Wiplan and NS3.* The MobiSim ADT and iPlan projects involve Guillaume Villemaud (axis 1) and Jean-Marie Gorce (axis 2).
- *Resource allocation and architecture of low power multi-band front-end.* The EconHome project involves people from axis 2 (Jean-Marie Gorce,Nikolai Lebedev) and axis 1 (Florin Hutu).
- *Virtual machine for SDR.* In collaboration with CEA, a PhD started in October 2011, involving people from axis 3 (Tanguy Risset, Kevin Marquet) and Leti’s engineers closer to axis 2.
- *Relay strategy for cognitive radio.* Guillaume Villemaud and Tanguy Risset were together advisers of Cedric Levy-Bencheton PhD Thesis (defense last June).

Finally, we insist on the fact that the *FIT project* will involve each member of Socrate and will provide many more opportunities to perform cross layer SDR experimentations. FIT is already federating all members of the Socrate team.

[1] Lyrtech (http://www.lyrtech.com) designs and sells radio card receivers with multiple antennas offering the possibility to implement a complete communication stack

../../../../projets/socrate/IMG/airelleCollab2014.png

Figure 5. Inter-Axis Collaboration in Socrate: we expect innovative results to come from this pluri-disciplinary research

URBANET Team

3. Research Program

3.1. Capillary networks

The definition of Smart Cities is still constantly redefined and expanded so as to comprehensively describe the future of major urban areas. The Smart City concept mainly refers to granting efficiency and sustainability in densely populated metropolitan areas while enhancing citizens' life and protecting the environment. The Smart City vision can be primarily achieved by a clever integration of ICT in the urban tissue. Indeed, ICTs are enabling an evolution from the current duality between the "real world" and its digitalized counterpart to a continuum in which digital contents and applications are seamlessly interacting with classical infrastructures and services. The general philosophy of smart cities can also be seen as a paradigm shift combining the Internet of Things (IoT) and Machine-to-Machine (M2M) communication with a citizen-centric model, all together leveraging massive data collected by pervasive sensors, connected mobile or fixed devices, and social applications.

The fast expansion of urban digitalization yields new challenges that span from social issues to technical problems. Therefore, there is a significant joint effort by public authorities, academic research communities and industrial companies to understand and address these challenges. Within that context, the application layer, i.e., the novel services that ICT can bring to digital urban environments, have monopolized the attention. Lower-layer network architectures have gone instead quite overlooked. We believe that this might be a fatal error, since the communication network plays a critical role in supporting advanced services and ultimately in making the Smart City vision a reality. The UrbaNet project deals precisely with that aspect, and the study of network solutions for upcoming Smart Cities represents the core of our work.

Most network-related challenges along the road to real-world Smart Cities deal with efficient mobile data communication, both at the backbone and at the radio access levels. It is on the latter that the UrbaNet project is focused. More precisely, the scope of the project maps to that of capillary networks, an original concept we define next.

The capillary networking concept represents a unifying paradigm for wireless last-mile communication in smart cities. The term we use is reminiscent of the pervasive penetration of different technologies for wireless communication in future digital cities. Indeed, capillary networks represent the very last portion of the data distribution and collection network, bringing Internet connectivity to every endpoint of the urban tissue in the same exact way capillary blood vessels bring oxygen and collect carbon dioxide at tissues in the human body. Capillary networks inherit concepts from the self-configuring, autonomous, ad hoc networks so extensively studied in the past decade, but they do so in a holistic way. Specifically, this implies considering multiple technologies and applications at a time, and doing so by accounting for all the specificities of the urban environment.

3.2. Specific issues and new challenges of capillary networks

Capillary networks are not just a collection of independent wireless technologies that can be abstracted from the urban environment and/or studied separately. That approach has been in fact continued over the last decade, as technologies such as sensor, mesh, vehicular, opportunistic, and – generally speaking – M2M networks have been designed and evaluated in isolation and in presence of unrealistic mobility and physical layer, simplistic deployments, random traffic demands, impractical application use cases and non-existent business models. In addition, the physical context of the network has a significant impact on its performances and cannot be reduced to a simple random variable. Moreover, one of the main element of a network never appears in many studies: the user. To summarize, networks issues should be addressed from a user- and context-centric perspective.

Such abstractions and approximations were necessary for understanding the fundamentals of wireless network protocols. However, real world deployments have shown their limits. The finest protocols are often unreliable and hardly applicable to real contexts. That also partially explains the marginal impact of multi-hop wireless technologies on today's production market. Industrial solutions are mostly single-hop, complex to operate, and expensive to maintain.

In the UrbaNet project we consider the capillary network as an ensemble of strongly intertwined wireless networks that are expected to coexist and possibly co-operate in the context of arising digital cities. This has three major implications:

- Each technology contributing to the overall capillary network should not be studied apart. As a matter of fact, mobile devices integrate today a growing number of sensors (e.g., environment sensing, resource consumption metering, movement, health or pollution monitoring) and multiple radio interfaces (e.g., LTE, WiFi, ZigBee,. . .), and this is becoming a trend also in the case of privately owned cars, public transport vehicles, commercial fleets, and even city bikes. Similarly, access network sites tend to implement heterogeneous communication technologies so as to limit capital expenses. Enabling smart-cities needs a dense sensing of its activities, which cannot be achieved without multi-service sensor networks. Moreover, all these devices are expected to inter-operate so as to make the communication more sustainable and reliable. Thus, the technologies that build up the capillary network shall be studied as a whole in the future.
- The capillary network paradigm necessarily accounts for actual urban mobility flows, city land-use layouts, metropolitan deployment constraints, and expected activity of the citizens. Often, these specificities do not arise from purely networking features, but relate to the study of city topologies and road layouts, social acceptability, transportation systems, energy management, or urban economics. Therefore, addressing capillary network scenarios cannot but rely on strong multidisciplinary interactions.
- Digital and smart cities are often characterized by arising M2M applications. However, a city is, before all, the gathering of citizens, who use digital services and mobile Internet for increasing their quality of life, empowerment, and entertainment opportunities. Some data flows should be gathered to, or distributed from, an information system. Some other should be disseminated to a geographically or time constrained perimeter. Future usage may induce peer-to-peer like traffics. Moreover these services are also an enabler of new usages of the urban environment. Solutions built within the capillary network paradigm have to manage this heterogeneity of traffic requirements and user behaviors.

By following these guidelines, the UrbaNet ambition is to go one step beyond traditional approaches discussed above. The capillary network paradigm for Smart Cities is tightly linked to the specificities of the metropolitan context and the citizens' activity. Our proposal is thus to re-think the way capillary network technologies are developed, considering a broader and more practical perspective.

3.3. Characterizing urban networks

Our first objective is to understand and model those properties of real-world urban environments that have an impact on the design, deployment and operation of capillary networks. It means to collect and analyze data from actual deployments and services, as well as testbeds experiments. These data have then to be correlated with urban characteristics, e.g. topography, density of population and activities. The objective is to deduce analytical models, simulations and traces of realistic scenarios that can be leveraged afterward. We structure the axis into three tasks that correspond to the three broad categories of networking aspects affected by the urban context.

- **Topological characteristics**. Nowadays, the way urban wireless network infrastructures are typically represented in the literature is dissatisfying. As an example, wireless links are mostly represented as symmetric, lossless channels whose signal quality depends continuously on the distance between the transmitter and the receiver. No need to say, real-world behaviors are very far from these simplified representations. Another example, topologies are generally modeled according to deterministic (e.g., regular grids and lattices, or perfect hexagonal cell coverages) or stochastic (e.g., random uniform distributions over unbound surfaces) approaches. These make network problems mathematically tractable and simulations easier to set up, but are hardly representative of the layouts encountered in the real world. Employing simplistic models helps understanding some fundamental principles but risks to lead to unreliable results, both from the viewpoint of the network architecture design and from that of its performance evaluation. It is thus our speculation that the actual operations and the real-world topologies of infrastructured capillary networks are key to the successful deployment of these technologies, and, in this task, we aim at characterizing them. To that end, we leverage existing collaborations with device manufacturers (Alcatel-Lucent, HiKob) and operators (Coronis, Orange), as well as collaboration such as the Sense City project and testbed experiments, in order to provide models that faithfully mimic the behavior of real world network devices. The goal is to understand the important features of the topologies, including, e.g., their overall connectivity level, spatial density, degree distribution, regularity, etc. Building on these results, we try to define network graph models that reproduce such major features and can be employed for the development and evaluation of capillary network solutions.

- **Mobilities**. We aim at understanding and modeling the mobile portion of capillary networks as well as the impact of the human mobility on the network usage. Our definition of “mobile portion” includes traditional mobile users as well as all communication-enabled devices that autonomously interact with Internet-based servers and among themselves. There have been efforts to collect real-world movement traces, to generate synthetic mobility dataset and to derive mobility models. However, real-world traces remain limited to small scenarios or circumstantial subsets of the users (e.g., cabs instead of the whole road traffic). Synthetic traces are instead limited by their scale and by their level of realism, still insufficient. Finally, even the most advanced models cannot but provide a rough representation of user mobility in urban areas, as they do not consider the street layout or the human activity patterns. In the end, although often deprecated, random or stochastic mobility models (e.g., random walks, exponential inter-arrivals and cell residence times) are still the common practice. We are well aware of the paramount importance of a faithful representation of device and user mobility within capillary networks and, in order to achieve it, we leverage a number of realistic sources, including Call Detail Records (CDR) collected by mobile operators, Open Data initiatives, real-world social network data, and experiments. We collect data and analyze it, so as to infer the critical properties of the underlying mobility patterns.
- **Data traffic patterns**. The characterization of capillary network usages means understanding and modeling when, where and how the wireless access provided by the diverse capillary network technologies is exploited by users and devices. In other words, we are interested in learning which applications are used at different geographical locations and day times, which urban phenomena generate network usage, and which kind of data traffic load they induce on the capillary network. Properly characterizing network usages is as critical as correctly modeling network topology and mobility. Indeed, the capillary networks being the link directly collecting the data from end devices, we cannot count on statistical smoothing which yields regular distributions. Unfortunately, the common practice is to consider, e.g., that each user or device generates a constant data traffic or follows on/off models, that the offered load is uniform over space and does not vary over time, that there is small difference between uplink and downlink behaviors, or that source/destination node pairs are randomly distributed in the network. We try to go further on the specific scenarios we address, such as smart-parking, floating car data, tele-metering, road traffic management of pollution detection. To that end, we collect real-world data, explore it and derive properties useful to the accurate modeling of content consumption.

3.4. Autonomic networking protocols

While the capillary networks concept covers a large panel of technologies, network architectures, applications and services, common challenges remain, regardless the particular choice of a technology or architecture.

Our record of research on spontaneous and multi-hop networks let us think that autonomic networking appears as the main issue: the connectivity to Internet, to cyber-physical systems, to Information Systems should be transparent for the user, context-aware and location-aware. To address these challenges, a capillary network model is required. Unfortunately, very few specific models fit this task today. However, a number of important, specific capillary networks properties can already be inferred from recent experiments: distributed and localized topologies, very high node degree, dynamic network diameter, unstable / asymmetric / non-transitive radio links, concurrent topologies, heterogeneous capabilities, etc. These properties can already be acknowledged in the design of networking solutions, and they are particularly challenging for the functioning of the MAC layer and QoS support. Clearly, capillary networks provide new research opportunities with regard to networking protocols design.

- **Self-* protocols**. In this regard, self-configuration, self-organization and self-healing are some of the major concerns within the context of capillary networks. Solving such issues would allow spontaneous topologies to appear dynamically in order to provide a service depending of the location and the context, while also adapting to the interactions imposed by the urban environment. Moreover, these mechanisms have the capacity to alleviate the management of the network and the deployment engineering rules, and can provide efficient support to the network dynamics due to user mobility, environment modifications, etc. The designed protocols have to be able to react to traffic requests and local node densities. We address such self-adaptive protocols as a transversal solution to several scenarios, e.g. pollution monitoring, smart-services depending on human activities, vehicle to infrastructure communications, etc. In architectures where self-* mechanisms govern the protocol design, both robustness and energy are more than ever essential challenges at the network layer. Solutions such as energy-harvesting can significantly increase the network lifetime in this case, therefore we investigate their impact on the mechanisms at both MAC and network layers.
- **Quality of service issues**. The capillary networks paradigm implies a simultaneous deployment of multiple wireless technologies, and by different entities (industry, local community, citizens). This means that some applications and services can be provided concurrently by different parts of the capillary network, while others might require the cooperation of multiple parties. The notion of Service Level Agreement (SLA) for traffic differentiation, quality of service support (delay, reliability, etc.) is a requirement in these cases for scalability purposes and resource sharing. We contribute to a proper definition of this notion and the related network mechanisms in the settings of low power wireless devices. Because of the urban context, but also because of the wireless media itself, network connectivity is always temporary, while applications require a delivery ratio close to 100%. We investigate different techniques that can achieve this objective in an urban environment.
- **Data impact**. Capillary networks suffer from low capacity facing the increasing user request. In order to cope with network saturation, a promising strategy is to consider the nature of the transmitted data in the development of the protocols. Data aggregation and data gathering are two concepts with a major role to play in this context of limited capacity. In particular, combining local aggregation and measurement redundancy for improving on data reliability is a promising idea, which can also be important for energy saving purposes. Even if the data flow is well known and regular, e.g. temperature or humidity metering, developing aggregation schemes tailored to the constraints of the urban environment is a challenge we address within the UrbaNet team. Many urban applications generate data which has limited spatial and temporal perimeters of relevance, e.g. smart-parking applications, community information broadcasting, etc. When solely a spatial range of relevance is considered, the underlying mechanisms are denoted “geocasting”. We also address these spatio-temporal constraints, which combine geocasting approaches with real-time techniques.

3.5. Optimizing cellular network usage

The capacity of cellular networks, even those that are now being planned, does not seem able to cope with the increasing demands of data users. Moreover, new applications with high bandwidth requirements are also foreseen, for example in the intelligent transportation area, and an exponential growth in signaling traffic is expected in order to enable this data growth. Cumulated with the lack of available new spectrum, this leads to an important challenge for mobile operators, who are looking at both licensed and unlicensed technologies for solutions. The usual strategy consists in a dramatic densification of micro-cells coverage, allowing both to minimize the transmission power of cellular networks as well as to increase the network capacity. However, this solution has obvious physical limits, which we work on determining, and we propose exploiting the capillarity of network interfaces as a complementary solution.

- **Green cellular network**. Increasing the density of micro-cells means multiplying the energy consumption issues. Indeed, the energy consumption of actual LTE eNodeBs and relays, whatever their state, idle, transmitting or receiving, is a major and growing part of the access network energy consumption. For a sustainable deployment of such micro-cell infrastructures and for a significative decrease of the overall energy consumption, an operator needs to be able to switch off cells when they are not absolutely needed. The densification of the cells induces the need for an autonomic control of the on/off state of cells. One solution in this sense can be to adapt the WSN mechanisms to the energy models of micro-cells and to the requirements of a cellular network. The main difficulty here is to be able to adapt and assess the proposed solutions in a realistic environment (in terms of radio propagation, deployment of the cells, user mobility and traffic dynamics).
- **Offloading**. Offloading the cellular infrastructure implies taking advantage of the wealth of connectivity provided by capillary networks instead of relying solely on 4G connectivity. Cellular operators usually possess an important ADSL or cable infrastructure for wired services, the development of femtocell solutions thus becomes very popular. However, while femtocells can be an excellent solution in zones with poor coverage, their extensive use in areas with a high density of mobile users leads to serious interference problems that are yet to be solved. Taking advantage of capillarity for offloading cellular data relies on using IEEE 802.11 Wi-Fi (or other similar technologies) access points or direct device-to-device communications. The ubiquity of Wi-Fi access in urban areas makes this solution particularly interesting, and many studies have focused on its potential. However, these studies fail to take into account the usually low quality of Wi-Fi connections in public areas, and they consider that a certain data rate can be sustained by the Wi-Fi network regardless of the number of contending nodes. In reality, most public Wi-Fi networks are optimized for connectivity, but not for capacity, and more research in this area is needed to correctly assess the potential of this technology. Direct opportunistic communication between mobile users can also be used to offload an important amount of data. This solution raises a number of major problems related to the role of social information and multi-hop communication in the achievable offload capacity. Moreover, in this case the business model is not yet clear, as operators would indeed offload traffic, but also lose revenue as direct ad-hoc communication would be difficult to charge and privacy issues may arise. However, combining hotspot connectivity and multi-hop communications is an appealing answer to broadcasting geo-localized informations efficiently.