# Research Report
# 2005-2009
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# Télécom ParisTech / LTCI

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Laboratoire Traitement et Communication de l'Information - UMR 5141
Télécom ParisTech - CNRS

# Network and Computer Science

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# Contents

# Network and Computer Science (INFRES)

During the period of this evaluation, the Networks and Computer Sciences Department was averaging about 50 permanents including faculty and engineers. Its growth stayed modest with an increase of one or two faculty or engineer each year. However in the same period of time its revenue growth was at a remarkable rate of over 30%. As for this year ending, despite the economic crisis, we are forecasting a 5% growth in revenue. As a consequence, counting in term of FTFE (Full Time Faculty Equivalent, who are clearly responsible for getting most of our research contracts and grants), the ratio revenue per FTFE has been growing similarly to reaching nearly 150k€ this year from about 80k€ at the beginning of this evaluation.

The Networks and Computer Sciences Department has a long tradition of studying complex network or software system architectures. Both complex network systems and complex software systems are constrained by a series of classical common high level requirements including: scalability, quality of service, availability, maintainability, safety, security, dependability, usability, and of course performance and cost saving. Today, energy saving and durability would certainly have to be added to the list, even if they are not really as new as it would seem. Fortunately, this list changes very slowly. However, system elements change fundamentally and at a fast pace: links between nodes became optical or wireless. This allowed nodes to become mobile, to appear, disappear, and reappear at another end of the network. Networks are becoming networks of 'things' as they include all kind of cell phones, sensors, RFIDs or even robots (like drones). These things can be more or less ubiquitous, more or less autonomous. Let's stop here for a moment and describe later our vision for the research in the Department; this rapid landscape should be sufficient to explain how research is led in the Department. For instance, one specific category of system could have been chosen and thoroughly studied under the entire variety of high level requirements. Instead, it has been chosen to focus on the various 'Gordian' knots found in complex software systems and networks that have high scientific value and make these systems or networks difficult to develop, maintain, and control.

For instance, how to process and analyze a large amount of data 'on the fly' as they arrive from multiple nodes? How to efficiently search through a vast heterogeneous set of data more or less reliable over the web? How to rapidly develop and verify a real time system re-using existing components? What kind of middleware can support collaborative applications over a wireless self-configuring network? How to broaden the interaction with a computing device using solely the movement of a thumb? All these various questions are illustrating part of the research led in the **Information Systems and complex systems (IC2&S3) Group**.

Sometimes good common sense and solid methodologies are just not enough. When it is about pushing the constraints over the requirements described above to the limits of what physics can offer, for instance using quantum theory to establish the highest level of security possible. When it is about providing with the best tools possible allowing designing the best network architecture to fight in the fierce economy of the telecommunication industry, for instance making some advance in probability theory using the Malliavin calculus. When it is about optimizing an optical network using graph theory or linear programming elevating drastically technology barriers. Discrete or not, mathematics are impassable and are a key component in the research

led in the Department. Members of the **Mathematics of Information, Communication, and Computation (MIC2) Group** are dedicated to this critical effort.

Last but not least, the members of the **Networks, Mobility, and Security Group** are studying a broad variety of network architectures (P2P, mobile, mesh, or hybrid,...) going from the core layers of the communication network to the service layers: establishing how congestions can be avoided, looking at various architectures and making contributions to new protocols able to transport data, voices, images, or video; analyzing QoS or performance; managing mobility or radio resource; revisiting scheduling or failover algorithms. At last, in order to conduct its research in the domain of security, the group is mastering a large array of technologies spanning from novel usages of the smart card to game theory.

To succeed, the Department is demanding more than *just* publishing even important books like the J. Sakarovitch's one. To reach critical mass, it is participating to common labs like UBI-Media with Alcatel-Lucent, BiLab with EdF today extended to France Telecom and Inria, or more recently with the LInC with UPMC, Inria, and Thomson. It has constant and noticeable contributions to many industry standards (AADL just to pick one in the domain of embedded systems), an increased number of patents and public domain software. It also has a strong contribution to the Telecom ParisTech curriculum as well as the program of continuing education. At last, the Department has been able to create two start-ups SeQureNet and Ether Trust both in the domain of security.

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|---|---|
| Faculty [IT, CNRS] | [37.8, 3.2] |
| PhD students | 56.5 |
| Post-docs, engineers and sabbaticals | 14.3 |
| Defended PhD theses | 71 |
| Defended HDR | 5 |
| Journal papers | 155 |
| Papers in conference proceedings | 608 |
| Chapters and books | 66 |
| Patents and software | 35 |
| Grants [public, private, european] (k€) | [7691, 3746, 3022] |

# Chapter 1

# Information Systems and Complex Systems (IC2/S3)

**Team leaders** I. Demeure (P), G. Hebrail (P).

**Faculty** T. Abdessalem (MC), P. Bellot (P), B. Burtschy (P), B. Cautis (MC, 10/07–), A. Danzart (MC), J.L. Dessalles (MC), A. Grumbach (P, –10/08), Y. Guiard (DR CNRS, 10/07–), G. Hebrail (P, 12/06–), J. Hugues (MC), E. Lecolinet (MC), A. Mari (CR CNRS, –09/05), E. Najm (P), G. Origgi (CR CNRS, –09/05), L. Pautet (P), J.M. Saglio (DE, –01/07), C. Potier (MC), F. Rossi (MC, 09/08–), P. Senellart (06/08–), S. Tardieu (MC), S. Vignes (MC), F. Yvon (MC, –08/07).

**PhD students** M. Baglioni (11/09–), G. Bailly (11/06–05/09), K. Barbaria (10/05–12/08), E. Borde (12/06–), R. Chiky (10/05–01/09), B. Csernel (CIFRE 11/04–02/08), J. Delange (10/07–), N. Derouiche (10/08–), A. Dimulescu (10/08–), N. Gabsi (CIFRE 11/07–), O. Gilles (03/07–), X. Grehant (10/06–), B.Gueni (10/05–), H. Ha Duong (10/06–), I. Hamid (02/05–05/08), J. Hugues (10/02 – 09/05), Z. Kazi-Aoul(10/03–2/08), G. Lasnier (10/08–), S.Malacria (11/08–), S. Naqvi (10/02–12/05), G. Paroux (CIFRE 10/04–06/09), I. Perseil (10/05–), X. Renault (1/2007–), A. Roudaut (11/07–), M. Tahir (12/06–07/09), T. Vergnaud (10/03–11/06), Y. Yu (01/07–12/07), B. Zalila (10/05–11/08).

**Post-docs, engineers and sabbaticals** G. Bailly (06/09-05/10), N. Benguigui (délégation CNRS, 10/08-09/09), R. Blanch (12/05-09/06), P. Busch (Technician), P. Dax (DE, acting as research engineer), B. Dupouy (MC, acting as research engineer), P. Feiler (CMU-SEI 04/08–06/08), S. Ferrandiz (02/07–11/07), S. Gadret (CE), S. Gardoll (CNRS engineer, 01/09–), S. Huot (02/06-01/07), K. Jouini (08/08-07/09), K.P. Maalej (11/07-01/09), G. Mouret (Research engineer), H. Olafsdottir (10/08–), A. Tabard (04/09–), S. Tardieu (MC, acting as research engineer).

**External collaborators** A. Cotton (Thales Communications), A. Fantechi (Univ. Florence), P. Feiler (CMU/SEI), A. Galland (PhD student, INRIA Saclay), S. Jarp (CERN), E. Kharlamov (PhD student, Free University of Bozen-Bolzano & INRIA Saclay), F. Kordon (LIP6/MoVe),F. Singhoff (UBO), P. Toft (HP Labs, Bristol).

| | |
|---|---|
| Faculty [IT, CNRS] | [14.3 [1], 0.7] |
| PhD students | 12.6 |
| Post-docs, engineers and sabbaticals | 7 |
| Defended PhD theses | 20 |
| Defended HDR | 1 |
| Journal papers [published, in press] | [30, 3] |
| Papers in conference proceedings | 273 |
| Chapters and books | 32 |
| Patents and sofware | 15 |
| Grants [public, private, european] (k€) | [2553, 1325, 254] |

[1] This number figures the yearly average number of IT faculties. It should be divided by 2 to take into account that IT faculties dedicate half of their time to teaching.

## 1.1 Objectives

This section reports on the research work accomplished both within the IC2 and the S3 groups. The decision to federate both groups in one report was taken because although S3 is about the same size as the other groups nevertheless only a small half of the members of S3 are active in research while the other half consists in engineers and technicians providing operational network and system support to the INFRES department. It therefore seemed appropriate to present altogether the research accomplished in the computer science field within the INFRES department.

The research activity of the team focuses on Information Systems and their architecture, in their various forms: Distributed, Ubiquitous, Data Intensive, Complex, Web based, Real Time and Embedded; the team has important contributions to the main tiers that constitute these Systems: Human Computer Interfaces, Middleware, Data Bases and Services. Hence, the main challenges addressed by the team are related to:

- the mobile and highly distributed nature of today systems which stresses problems of reliability, connectivity, data sharing and coherence
- the monotonic growth of data that needs to be combined with more flexible structures (both on the web and within large companies)
- new levels of software complexity for which there is a strong need for new software engineering techniques (complexity and scalability on the number of components in enterprise IS and web services, reliability in embedded systems)
- the human computer interfaces which is a critical factor of acceptance and usage of computerized systems.

These challenges are cross-disciplinary: from a practical point of view, the activity of the team has been developped along the following dimensions:

- (1) Business Intelligence for Enterprise Information Systems;
- (2) Databases: management of web data, distributed management of trust and data access;
- (3) Middleware: that needs to be adaptive in many different ways;

- (4) Software Engineering for distributed real-time embedded systems: which is model based, taking advantage of formal semantics and supporting transformation tools;
- (5) Human Computer Interaction : mobile interaction, manipulation of a large amount of data.

Dimension (1) and partially dimension (2) are mainly related with the application level of Information Systems. Dimensions (2) and (3) cover the technical architecture of IS. Dimensions (4) and (5) are related to the design of IS. The objectives within each dimension, together with corresponding basic research are developed and described below.

Business Intelligence (BILAB Project)
The activity of the BILab Project covers several aspects of the Business Intelligence field in relation to both theoretical approaches and industrial applications. The two main challenges we address are (1) facing the increasing volume of available data to feed BI systems and (2) the need for almost real time reporting on the enterprise activity. Consequently, a major activity during the period has been related to data stream processing. Data stream processing has been studied intensively recently is to process data *on the fly* as they arrive instead of storing them beforehand in a data warehouse. This approach is referred as Data Stream Querying (if the goal is to query data) or Data Stream Mining (if the goal is to mine data).

Within this context, the BILab Project developed a research activity in this domain which is very active in the USA but not yet in Europe, and focussed on summarizing the history of data streams. Indeed, all existing data stream processing approaches can only provide results from the part of the stream posterior to the definition of queries or mining tasks.

Industrial applications mainly cover the telecommunication and energy fields.

Databases and the World Wide Web (DBWeb Project)
In this project, we study the fundamental issues raised in modern data and knowledge management systems, especially on the World Wide Web and in collaborative contexts oriented towards peer-to-peer networks. Research interests cover theoretical foundations as well as practical solutions and applications of data and knowledge management systems. The main challenges we address are:

- Query optimization over structured or semi-structured data,
- Web data management, with heterogeneous data, with restricted access patterns (deep Web), uncertain and contradictory data,
- Mining of very large graphs, and in particular of the Web graph,
- Relevance in communication and its applications in modern knowledge management systems,
- Distributed management of trust and data access in large information-sharing networks,
- Data management for mobile sensors.

Adaptable middleware
Existing middleware technologies for Mobile Ad hoc Networks applications (MANet) or Distributed Real time Embedded Systems (DRE) (such as TAO) provide general purpose execution platforms targeting a large spectrum of application domains. Their complex design patterns induce large memory footprints and execution overheads but also produce systems that are difficult to analyse and verify.

Our research is precisely aimed at addressing this pitfall. Our goal is to produce a verifiable and highly configurable middleware factory. The sought and delivered factory should be based

on a flexible, modular and versatile architecture that allows for the automated generation of middleware instances matching specific application requirements. This endeavour involves also the design and delivery of predefined or automatically generated components that support specific distribution and communication functions. The factory should allow for the verification of these individual components as well as their sound integration in the delivered middleware.
General purpose middleware also fail to resolve MANet specific needs. A MANet is a self-configuring network of mobile nodes connected by wireless links. MANets are highly dynamic. Changes may impact network topology in many ways - nodes may become out of reach of each other, or may have energy failures. Hence servers must be redundantly distributed over the nodes. The supporting middleware must manage dynamic service location and routing. Thus they must monitor the topology and adapt with appropriate actions. They must also preventively manage power consumption by monitoring and balancing node activities. These are the goals we pursued in designing middleware for MANets.

Model driven development
Our main endeavour is to define and build a development process, endowed with a supporting transformational tool chain, that aims at producing systems that faithfully implement high-level requirements. Mode Driven Engineering (MDE) is a key enabling technology: models are versatile as they can describe various software and system engineering artefacts: from requirements down to resources, platforms, application components, infrastructure components, etc. The applicability of MDE to Distributed Real time Embedded sytems(DREs) has not been properly addressed yet by the research community.

Our aim is precisely to bring the potential benefits of MDE to reality in the realm of DREs and safety critical systems. Thus, the sought and delivered tool chain has distinctive features that are hard to obtain in DREs.

Cost reduction and higher quality are to be achieved by extending the automatic code generation capabilities to distributed code and to the automatic deployment of the system. It is to be achieved also by allowing for the integration of predefined components (COTS) in the transformational process. Such an automatic code generation allows to produce the optimized and analyzable components of PolyORB-HI, our DRE AADL middleware (previously described). System quality and correctness is to be enhanced by the use of formal verification of both the functional (deadlock/starvation non-appearance) and non-functional (schedulability, response time) properties of systems.

The delivered process should address and integrate the different domains of expertise that are involved in building complex space and avionics systems, from requirmements capture, through formal modeling and property assessment, down to to the final impementations.

Advanced Interaction and Visualization (VIA Project)
This project is devoted to fundamental and applied research on Human Computer Interaction (HCI). It focuses on the double challenge of representing and manipulating more and more data, and to allow this not only on standard computers but also on small, mobile and non traditional devices. Our main contributions take place in the following domains:

- Novel interaction techniques and principles, with an emphasis on leveraging input dimensions that had been overlooked so far,
- Mobile interaction, with a special effort toward increasing the ”interaction bandwidth” between users and their devices (tablets, iphone, ...),
- Information visualization, and more specifically interactive visualization, which aims at allowing users to explore and manipulate the data actively,

- Fundamental HCI research on simple reaching movements, overwhelmingly frequent in HCI, with a project aimed at providing a more general understanding of the Fitts' law.

## 1.2 Main Results

### 1.2.1 Business Intelligence (BILab)

**Faculty** B. Burtschy, A. Danzart, G. Hebrail, C.Potier, F. Rossi, S. Vignes.

**Main events** Organization of several workshops: *Temporal data mining* at EGC2008 and EGC2009; *28th International Symposium on Forecasting (ISF)*, Nice, France, June 2008; *International Workshop on data stream management and mining*, University of Beihang, Beijing, October 2008; *European Workshop on Data Stream Analysis*, University of Naples, Caserta, March 2007; 14th Annual Conference of the Société Francophone de Classification (with the MIC2 team of INFRES), September 2007.

**Projects** ANR MDCO MIDAS (2008-2010).

**Industrial collaborations** Orange Labs (2 CIFRE PhD students, EDF R&D (BILab: a joint research laboratory on BI created in 2007).

Since 2007, most of the activity related to BI is inscribed into a new joint research laboratory with the research centre of EDF (Electricité de France). This laboratory is called the BILab (see `http://bilab.enst.fr`). This collaboration enables closer relationship with a large industrial company. During year 2009, the BILab is extending to another large industrial company (Orange Labs) and another research organization (INRIA, Axis Project). This extension is a great opportunity for our project because both EDF and Orange are very large companies having real practical problems related to managing a huge amount of data in a BI perspective. EDF data is mainly related to electrical power consumption of all customers which will be available massively with the development of smart meters. Orange data is also related to the usage of services by customers, both on telecommunication calls and internet access.

Data stream management

Data stream management systems (sometimes called complex event processing systems) are systems which extend the standard database technology to query data available in the form of streams of structured records. We developed a prototype with one of the first commercial DSMS (STREAMBASE) which processes electrical power consumption data available from electrical power smart meters [216]. Still in the context of electrical power smart meters, a new data model was defined to transmit data from households to the utility information system. This data model describes appliances of the household and their usage in terms of *On/Off* events. A simulator of such events was also designed and developed to generate a data stream from each household. Generated streams are captured by a Data Stream Management System in order to show that few basic queries are sufficient to supervise the household electrical power consumption [96] .

Our main activity related to data stream processing focuses on summarizing structured data streams: this requires the summaries to be built incrementally with little computation for each record and bounded or slowly growing disk space for storage. We developed several new approaches to summarize one or several structured data streams:

- *Streamsamp*: a random sampling approach which summarizes a unique stream but is combined with a technique which decreases the precision (and thus the storage space) for older data [79]. Several experiments have shown the efficiency of this algorithm however its accuracy decreases with very old data. In order to solve this issue, an hybrid approach has been developed and assessed: it combines the streamsamp algorithm with another existing algorithm (clustream) based on micro-clustering [190].

- *Crosstream*: an approach which summarizes three related streams. Two streams contain information about two different entity types and the third stream contains information about the relationships between entities [222].
- A temporal sampling approach applicable to a large number of distributed streams all producing the same type of information. The temporal sampling is adaptive and optimized to provide good precision on aggregation of any subset of the streams. The optimization is performed in relation to: (1) a maximum available bandwidth for stream transmission, (2) individual values of each stream. This approach has been applied and assessed on time series issued by electric power meters [78].

Beyond the definition of these algorithms, much work has been done on designing new ways of evaluation of the accuracy/precision of the summaries, and running comprehensive experiments both on artificial and real data. Indeed, standard assessment methodologies had to be revisited to take into account the temporal evolution of data inherent to streams.

Finally, a first study was carried out on the management of OLAP data cubes fed by one or several streams. A load shedding method was designed to sample randomly incoming data, in order to be able to continue to feed the cube when the input rate is too high. Confidence intervals on queries on such a data cube were theoretically defined [189].

Time series and functional data mining

BI deals frequently with time varying objects. Such objects are better understood as functional data: each object is described by some functions that map time to appropriate values describing the object on a given dimension at the specified date. Rather than analysing snapshots of the objects, one handles their complete evolution through time by targeting directly the functions.

We provide exploratory analysis of functional datasets via a combined clustering and segmentation approach. Functions are clustered into homogeneous clusters with the specific property that each cluster is represented by a simple functional prototype, for instance a piecewise constant function. The complexity of the prototype set (e.g., the total number of constant parts) is globally optimized by an efficient dynamic programming scheme [109]. Related work include [128] in which a piecewise constant approximation of functional data is built in a supervised manner: one finds a simplified representation optimized according to an external criterion (such as the ability to separate efficiently two classes of functions).

In [238], we handle time varying data in a quite different manner: in this case, the evolution through time of an unique system (a web server) is studied. A time aware clustering algorithm is used to track the evolution of the web server usage patterns.

Several approaches related to time series modelling, analysis and forecasting have also been developed, with applications in the domain of software reliability (see [135], [137], [136], [165], [30], [44]).

Web and social network mining

We have recently started to work on exploratory analysis of social networks and proposed in [155] a new clustering method for graphs. It produces communities that optimize a trade-off between a graph clustering quality measure (Girvan and Newman's Modularity measure) and a visualization quality measure inspired by the self organizing map algorithm. The method results in a coarse grained graph that is both a faithful simplification of the original graph and easy to represent and draw.

### 1.2.2 Databases and the World Wide Web (DBWeb)

**Faculty** T. Abdessalem, B. Cautis, J.-L. Dessalles, P. Senellart.

**Main events and external collaborations** Ongoing collaborations on XML data management with the Database group of University of California San Diego (Alin Deutsch) and Athens University of Economics and Business (Vasilis Vassalos).

Ongoing collaborations on data exchange, probabilistic databases, and the deep Web with the University of Oxford and INRIA-Saclay GEMO project (Serge Abiteboul).

Extended research stay of P. Senellart at Max-Planck-Institut für Informatik (Saarbrücken, Germany).

**Projects** ANR DataRing (2009–2011), ANR ISICIL (2009–2011), ANR LPOD (2009–2010), ANR PANIC (2010–2012), Advanced ERC Project Webdam (2009–2013), Webograph (Institut TELECOM, 2007), Confidence (Institut TELECOM, 2008), Ranking of RSS streams (LIP6/Télécom ParisTech, 2009).

We study the problem of querying data sources that accept a limited set of queries, such as sources accessible by Web services which can implement very large (potentially infinite) families of queries. For the relational data model, we revisited in [13] a classical setting in which the application queries are conjunctive queries and the source accepts families of (possibly parameterized) conjunctive queries specified as the expansions of a (potentially recursive) Datalog program with parameters, under the assumption that sources satisfy integrity constraints. For semi-structured databases, we study in [14] the problem of querying XML data sources that accept only a limited set of queries, such as sources accessible by Web services which can implement very large (potentially infinite) families of XPath queries.

As part of the work on XML query optimization, we proposed a rewriting algorithm that exploits minimization opportunities raised in composition-style nesting of queries [18, 229]. More precisely, we consider the simplification of XQuery queries in which the intermediate result constructed by a subexpression is queried by another subexpression, focusing on algorithms that can recursively prune query expressions, eliminating useless intermediate results. Still in the field of view-based query optimization, we study in [76] view-based rewriting for XPath in the presence of node identifiers or keys. We consider restrictions under which an XPath can be rewritten in polynomial time using an intersection of views and effective algorithms that can work for any documents or type of identifiers. Moreover, we consider the complexity of the related problem of deciding if an XPath with intersection can be equivalently rewritten as one without intersection or union.

We deal with the general problem of knowledge discovery and information extraction in the deep Web [167], and propose unsupervised and fully automatic techniques to perform an intensional (and not extensional) indexing thereof [27, 162]. For that purpose, we have the need to develop a probabilistic semi-structured data model that consists in annotating a tree-like document with conjunctions of literals representing independent probabilistic events. We study in depth the expressiveness of this model [26, 2], and propose efficient algorithms for querying and updating probabilistic data [62].

We develop techniques for the mining of large graphs: discovery of synonyms in the graph of a dictionary [265], of similar articles in that of an encyclopedia [24], of key actors in a collaboration network, prediction of the evolution of the World Wide Web graph, etc.

The extraction of complex data from semi-structured (HTML) sources is another recent direction of research of the group. We study techniques for template generation that exploit domain knowledge and semantics over the data.

In this project, we also carry on a basic research activity on relevance in communication in order to understand the foundations of modern knowledge systems. In our modelling work on relevance, we try to understand and predict what makes the content of a communicative act relevant. The ambition is to offer a predictive theory of what people talk about. This work has led to the *Complexity drop theory* [242]: interesting events are those which are less complex to describe than to generate (see: www.unexpectedness.eu). We could also formulate a *Generative theory of relevant argument* [90]. Lastly, we designed a model in which relevant communication is possible between non-cooperative (selfish) agents [241]. In this model, relevant communication is profitable to the emitter because it advertises definite qualities (relevance) that are appraised by listeners.

Still related to human aspects of modern knowledge systems, we work on the management of trust and access control in open contexts such as collaborative environments and social tagging platforms (Flickr, Del.icio.us, CiteUlike, etc). In particular, we are interested in the mechanisms by which trust (or distrust) relations between users can be built based on user activities, thematic proximity, reputation and peer evaluation, social links, and so on.

Finally, we work on spatio-temporal data streams and location service applications [60, 215]. We analyzed the necessity of a spatial windowing over spatio-temporal data streams and, based on the query language CQL (Continuous Query Language), we propose a appropriate syntax and formal semantics for spatial windowing operations.

Additional and up to date information on DbWeb main results and publications can be found on the project web page http://dbweb.enst.fr

### 1.2.3 Adaptable Middleware

**Faculty** I. Demeure, J. Hugues, L. Pautet.

**Main events and external collaborations** Summer school on Real Time Systems (ETR 09) by L. Pautet, France Telecom R&D, TAI/Thales, SC2/Thales, Agence Spatiale Europeenne (TOS-EME/ESA), Peter Feiler (SEI/CMU), Fabrice Kordon (LIP6/UPMC). Member of the SAE (Society of Automotive Engineers) ADL (Architecture Analysis Design Language) standard committee.

**Projects** ANR Flex-eWare, IST ASSERT, contracts with ESA and AdaCore RNRT-Transhumance, IST-POPEYE STREP, Contract with Orange R&D.

Adaptable middleware for distributed real time embedded systems

We study the problem of middleware engineering in the context of distributed real-time embedded (DRE) systems [255].

To tackle the middleware development complexity, we defined the schizophrenic middleware architecture. It makes it possible, for the first time, to instantiate simultaneously several distribution models with an excellent code reuse ratio compared to other approaches [111]. PolyORB, an implementation of this highly configurable architecture [112], is now industrially supported by AdaCore[1].

PolyORB is one of the very few middleware platforms to have been modelled and verified on some non-trival configurations using Petri nets (collaboration with LIP6/UPMC) in order to assess properties like deadlock free, livelock free or buffer dimensioning [254]. To improve the analysability of both the DRE system and its middleware, we decided to comply with the Ravenscar profile, a concurrency model for use in High-Integrity systems [112]. We also decided to use the Architecture Analysis and Description Language (AADL) (collaboration with SEI/CMU) to support our new design process for DRE systems [41].

We revisited PolyORB and the schizophrenic architecture [117] to define PolyORB-HI. It takes advantage of AADL to precisely deduce deployment and configuration information to automatically generate optimized and analyzable middleware components [171]. This AADL executive platform was one of the main results of the IST project ASSERT leaded by the European Space Agency, but also of the ANR Flex-eWare project. For instance, THALES reduced by a factor of 500 the memory footprint of executables produced with a concurrent approach. PolyORB-HI associated with our code generators is currently the first AADL execution platform for producing both Ada, C or RTSJ DRE systems.

We are studying the impact of new trends towards more complex DRE systems, like hierarchical partitioning as well as the duality of the safety and security features on middleware architecture. POK has enriched PolyORB-HI with safety (ARINC) and security (MILS) features coming from partitioned systems [83]. To our knowledge, POK is the first open-source kernel providing

[1] `http://www.adacore.com/home/products/gnatpro/add-on_technologies/distributed_systems`

both ARINC and MILS services. In the context of ANR Flex-eWare, we also made architectural improvements to enforce mode-based reconfiguration [72].

Adaptable middleware for collaborative applications over MANets
We designed and prototyped adaptable middleware solutions for Mobile Ad hoc Networks (MANets) providing support for collaborative applications. This led us to the following contributions.
*Publish-subscribe system for MANets*. Chapar is an event system designed for MANets [126]. It supports event persistency to resist transient disconnections and network partitioning. Following a cross-layer approach, Chapar relies on the Multipoint Relays (MPRs) defined in the OLSR MANet routing protocol as distributed brokers, and uses the OLSR routing table to disseminate the events. The support of persistency coupled with the cross-layer approach taking benefit from the OLSR MANet routing protocol, make Chapar quite unique.
*Data-sharing system for MANets*. Our system uses a predictive algorithm based on semantic information about the user and the data and previous access patterns to decide how to proactively replicate data. It creates enough replica to prevent data loss in case a peer unexpectedly disappears or a partition occurs. To this end, we proposed a stable group creation algorithm based on long lasting connectivity. While data sharing systems for MANET already exist, both the use of semantic information and of temporal stability are new in this domain. We illustrated the interest of the proposed algorithms by studying how a wiki service on MANETs would benefit from them [105], [104].
*Energy-aware middleware for MANets*. We proposed architectural guidelines, mechanisms and algorithms to design an energy aware middleware for MANets [211]. Each middleware module is designed with various level of functioning. When the energy level is high, the middleware provides all functionalities. When the energy level decreases, the functionalities are degraded in order to preserve the battery. The experiments performed showed a reduced energy consumption of about 20 % for the experiments conducted with ciphering and non acknowledged transport.
*Open source software*. Our contributions were prototyped and integrated to either one of the two platforms developed within the framework of POPEYE an IST STREP Project, and Transhumance an ANR RNRT project. Both platforms are available as open source software on Sourceforge. These developments were consucted jointly with our Transhumance and POPEYE partners and in particular with THALES present in both projects.
*Innovative demonstrators*. Finally, another contribution of this work lies in the cooperation with digital media designers (SES department) in order to propose innovative services, such as the above mentioned treasure hunting game, as demonstrators [98], [85].

A flexible architecture for the adaptation of composed multimedia
We proposed and prototyped PAAM (Provision of AdAptable Multimedia composed documents) a service oriented architecture for the adaptation of multimedia documents to user preference and context. A novelty in PAAM, with respect to related work, is that adaptors are offered as shared resources by the participants; hence PAAM is an example of peer-to-peer collaboration overlay that provides all the functionalities to declare, look for, select and compose adaptors located at participating peers. For the project purpose, we extended WSDL (Web Services Description Language) to describe adaptors in order to make them easily declared, looked-up and composed. We proposed a complete adaptation chain that was implemented using the web services technology [202].

### 1.2.4 Proof Based and Model Driven Developments

**Faculty** J. Hugues, E. Najm, L. Pautet, S Vignes.

**Main events** Organisation of AFADL'06 by S. Vignes; Neptune'08 et '09 by J. Hugues, S Vignes; FORTE'06, SDL'07 and ICSSEA'08 by E. Najm; IEEE/IFIP RSP'09 by J. Hugues

**Projects and** ACI FIACRE, ANR Flex-eWare, IST ASSERT, contracts with ESA and AdaCore,

ANR EDEMOI

Model based development for distributed real time embedded systems

We have built a combined expertise in modular middleware, formal modelling and software engineering. This wide range of expertise helps in delivering a full toolchain targeting the development of DREs.

We chose the AADL (Architecture Analysis and Design Language) as our pivot modelling language. AADL is an Architecture Description Language (ADL) well suited for DRE's. We have taken a leading position in the standardisation of this language, proposing several contributions to the core AADLv2 standard, and taking the lead on the definition of some annexes on data modeling, integration of programming languages, and on the integration of ARINC653 for the modeling of avionics system.

Based on AADL, We have designed a "Verification Driven Engineering" [127] process, where one iterates in order to enable verification at model level. We have shown that we need multiple formal methods to support the full engineering process. Therefore, we explored different tracks:

We adopted the Ada Ravenscar profile as one of our target patterns towards code generation, for its robustness and suitability for high-integrity systems as well as for its deterministic behaviour and its schedulability analysis capabilities.

We have defined the Ravenscar Meta Model (RMM) that we endowed with a formal semantics in order to make the generated code amenable for verification [107]. We have also defined a novel "deterministic" intertask commmunication pattern that we proved to be sound (cooperation with INRIA) [106]. We developed a prototype: ARC, to validate our transformations [40, 108].

We studied in collaboration with LIP6, the possibility to use Colored or Timed Petri Nets as another tool to support verification [153, 152] , and with UBO the possibility to perform high-level schedulability analysis of DREs.

We studied in collaboration with CMU/SEI the possibility to express safety and security properties on AADL model. We defined an AADL annex (REAL) [191] to express design patterns mandated by ARINC or MILS.

Ocarina [132] is the Open Source platform software that gathers our AADL tools and contributions. Ocarina has been tested and validated by academic and industrial partners as part of our funded R& D projects IST-ASSERT and ANR Flex-eWare in collaboration with ESA and Thales. Ocarina provides also a method for the integration of other modeling frameworks like SCADE or Simulink.

Proof based orchestration of web services

We defined a novel approach for the sound orchestration of services, based on expressing jointly behaviours and their types [97]. We proposed (1) Orcharts (orchestration charts) to define session based services and (2) Typecharts to support session types with complex interaction patterns that generalise the request/response interaction paradigm defined in BPEL. We defined an algorithm for deciding behavioural well typedeness and showed that it guarantees an important safety property: in all states of any configuration of well typed orcharts, all exchanged messages are expected and understood by their target partner.

Model based approach for formalising security properties

Our main contribution is a method to formalize security properties derived from the Goal-Oriented Requirements meta-method [134]. In this method, we match goals with security properties (for instance preventive security measures). We have adopted multiple notations to capture these properties: Natural language, a UML security profile, and formal methods (B and Z). Graphical UML descriptions are readable by domain experts and are used to support validation activities whereas formal methods are needed to support verification. Formal models are used to check the consistency of the documents and to generate test scenarios. The UML and formal models are tighly linked so as to make sure that "what you validate is that you verify".

We have applied our RE process and method to the domain of airport security (cf. EDEMOI Project). However, various domains including safety critical embedded system or ambient and pervasive adaptation, are concerned by confidence in the security properties and will be

confronted with certification activities.

### 1.2.5 Advanced Interaction and Visualization (VIA)

**Faculty** E. Lecolinet, Y. Guiard

**Main events** Official launching of the UBIMEDIA laboratory (2008); Conference organization (IHM 2006 and UBIMOB 2006: program co-chair), Special journal issue (Document Numérique, Hermès 2006)

**Projects** MOBA, MOBA2 then NIU projects with Alcatel-Lucent (12/05–; 2 theses), ANR XWiki Concerto (2006-2009), ANR TennisServer (2006-2009), iSphere (Institut Télécom; 2008), ENEIDE (Cap Digital; 2007-2010; 1 thesis), Quaero (OSEO; 2009-2013), Post-doc fundings by Region Ile-de-France (2007) and Carnot (2008-09).

**Collaborations** UBIMEDIA joint research lab with Alcatel-Lucent Bell Labs (created in 2008), co-direction of a PhD Student with L. Nigay (LIG), various research collaborations with INRIA/Aviz & INRIA/InSitu (Orsay), ESPCI/LOA, Paris8 PPCS & MISTIC, LIP6 (Paris), Université de Guanajuato (Mexique), other teams at TELECOM ParisTech (INFRES/S3, TSI/MM, SES/SHS, IP) and with the members of the projects we are involved in.

Our work on novel *interaction techniques* led us to develop new kinds of Marking menus, such as WaveMenus [65], FlowerMenus [66] and LeafMenus [158]. These techniques, based on gestural interaction, allow users to easily learn in novice (i.e., closed-loop) mode and later quickly execute in expert (i.e., open-loop) mode fairly large sets of commands. Gestural interaction is related to pattern recognition, especially handwriting recognition, a research field where we have collaborated with other researchers [11]. We have also worked on digital pen [208], tangible interfaces [141], tactile feedback [51] and developed hybrid devices that intermingle tangible interfaces and tactile feedback [143]. We also designed iSphere, a spherical input device currently under evaluation, aimed at facilitating interaction in 3D virtual worlds. Finally we recently introduced Motion-Pointing [17], a technique for selecting targets using elliptical motion instead of pointing. On these subjects, we have collaborated with various laboratories: LIG (a PhD thesis as been co-directed with L. Nigay), COSTECH (Compiègne), ESPCI LOA (Paris), INRIA AVIZ (Orsay)... and with colleagues from other teams at Telecom ParisTech (INFRES/S3, IP, TSI/MM).

We have developed several techniques specifically designed to facilitate *mobile interaction*, such as SpiraList [119] and SnailList [120], that use multi-scale spiral representations to minimize small-screen real estate. As an attempt to increase interaction bandwidth on common mobile devices, we proposed Tap-Tap, MagStick [159] and MicroRolls [25], which make it possible to interact very efficiently with the thumb. TapTap and MagStick outperform previous work on target acquisition on small devices while MicroRolls introduces a new set of gestures that enriches the input vocabulary of passive tactile surfaces. More recently, we also developed techniques based on 3D gestural interaction [157]. All these studies have been performed in collaboration with Alcatel-Lucent Bell Labs. They are also related to other partners of the UBIMEDIA laboratory, especially the SHS team (Telecom ParisTech SES).

In the Information visualization field, we introduced the concept of Zoomable Treemaps [3], a technique that makes it possible to navigate huge trees like the web base of the Open Directory project, with its 700,000 nodes. Another result in this category is the development of Perspective Drag [20] (in collaboration with INRIA InSitu) which leverages the familiar nonlinear variations of scale inherent in the perspective projection, and which we showed to help for navigating any sorts of large documents.

Finally, we have started casting some new light on Fitts' law, a famous empirical regularity of experimental psychology. In particular, we have clarified in what sense Fitts' law constitutes an instance of a speed-accuracy tradeoff [195]. We have also shown that the traditional definition of the independent variables involved in the law suffers a high degree of indeterminacy, and suggested a novel way of defining the basic dimensions of the problem [19].

It is important to note that people involved in the HCI activity have developed long-term collaborations with several industrial and academic partners: Alcatel Lucent Bell Labs (and the just launched UBIMEDIA joint research laboratory), LIG (Grenoble), INRIA InSitu and Aviz projects (Orsay), ESPCI LOA, Paris8 and LIP6 (Paris), COSTECH (Compiègne)... Moreover, VIA is an institutional project of Institut TELECOM that regroups researchers from other teams at Telecom ParisTech (INFRES/S3, TSI/MM, IP, SES/SHS) and Telecom SudParis (EPH). Many of them are also members of UBIMEDIA or other common projects.

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# Chapter 2

# Mathematics of Information, Communications and Computation (MIC$^2$)

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**Faculty** R. Alléaume (Ass. P.), P. Bourgade (Ass. P.), I. Charon (P.), G. Cohen (P.), L. Decreusefond (P.), E. Diamanti (CR CNRS) (01/09–), M. Gagnaire (P.), O. Hudry (P.), A. Lobstein (CR CNRS), D. Madore (Ass. P.) (09/07–), D. Markham (CR CNRS) (09/08–), N. Puech (Ass. P.)(–06/08) H. Randriambololona (Ass. P.), J. Sakarovitch (DR CNRS), A.S. Üstünel (P.).

**PhD students** S. Al Zahr (11/04–11/07), P.Y. Angrand (09/08–), R. Aoun (01/07–), D. Auger (10/07–), L. Belgacem-Denœud (11/03–11/06), A. Bocquet (09/08–),P. Bourgade (–01/09), I. Camilier (07/07–), C. Cardenas (01/07–), R. de Souza (10/04–10/08), E. Doumith (05/04–05/07), D. Elkouss (01/08–12/08), E. Ferraz (01/09–), J.P. Flori (09/08–), B. Kindarji (09/07–), A. Leverrier (09/06–), R. Medeiros (09/05–09/08), A. Morea (10/03–10/06), A. Pichot (04/05–04/08), J. Valentin (04/09–), T. Vu (09/08–), M. Youssef (09/08–).

**Post-docs, engineers and sabbaticals** S. Al Zhar (06/08–), B. Barbe (01/09–06/09), L. Belgacem-Denœud (03/07–03/08) , M. Dianati (07/07–06/08), E. Doumith (02/09–), P. Jouguet (03/09–), N. Skorin-Kapov (09/06–06/07).

**External collaborators** H. Chabanne, N. Puech, G. Zémor.

| | |
|---|---|
| Faculty [IT, CNRS] | [9.5, 2.5] |
| PhD students | 13 |
| Post-docs, engineers and sabbaticals | 2 |
| Defended PhD theses | 14 |
| Defended HDR | 1 |
| Journal papers [published, in press] | [63, 14] |
| Papers in conference proceedings | 62 |
| Chapters and books | 15 |
| Patents and software | 4 |
| Grants [public, private, European] (k€) | [892, 120, 419] |

## 2.1 Objectives

Our research is devoted to concepts, methods and models coming from mathematics, computer sciences , quantum mechanics. Our works are twofold: On the one hand, we apply abstract and generic mathematical results to the computer real world (biometry, optical networks, quantum networks, mobile networks). On the other hand, we consider new mathematical problems raised by the applications (differential geometry, algebraic geometry, automata, infinite dimensional calculus, quantum information). For instance, classic tools of combinatorial optimization, such as graphs and linear programming, are revisited for their applications to design and control of optical networks. We also strongly believe in the necessity to develop abstract theories like algebraic geometry or infinite dimensional analysis, in order to forge the tools which will be used in a near future to model and analyze more and more complex phenomenons.

## 2.2 Main Results

The main research results obtained during the period 2005-2009 are presented below for the research areas of the MIC$^2$ team.

### 2.2.1 Probability, Stochastic Modeling

**Faculty :** **P. Bourgade**, I. Camilier, **L. Decreusefond**, E. Ferraz, **A.S. Üstünel**, T. Vu.

**Projects :** *Projet structurant :* MONGE

- TROMATIC, CNRS Grant (01/06–12/06)
- CADRA, CNRS Grant (01/08–12/08)

Historically, the team was interested in analysis in infinite dimension, mainly Malliavin calculus and nuclear spaces, and its applications to telecommunications networks. Since the arrival of P. Bourgade, our themes widened to random matrices and number theory.

The optimal transportation problem dates back to the eighteenth century. Its modern approach was introduced in the forties by Kantorovitch as an optimization problem in a space of probability. A full solution for the quadratic cost was found in the nineties by Y. Brenier. Because of its numerous applications, for instance to functional inequalities, it is sensible to look at a generalization of this problem to infinite dimension spaces. The optimal transportation problem for a singular quadratic cost on the Wiener space was solved in [307, 347]. The results are formally identical

to those known in finite dimension but the lines of proofs are radically different. Consequences of these works are to be found in [345, 348, 349, 344]. In particular, we found necessary and sufficient conditions for a perturbation of the identity to be invertible in the Wiener space. We also gave some applications to filtering theory.

The mathematical properties of point processes are well known only for a very few number of processes. Unfortunately, in real life, it is seldom true that the real phenomenon can be modeled precisely by one of the known processes. It is thus of the utmost importance to quantify how far we are from the reality when we replace the "natural" process by a mathematically tractable one. It turns out that the optimal transportation problem for point processes gives an approach to this sort of problem. We solved it in [298]. Strangely enough, the methods are similar to those used in the Wiener space. One can now estimate the distance between Poisson point processes and several kind of processes like Cox processes, Markov modulated processes, Gibbs processes. Two articles are submitted about this topic.

As said above, a natural consequence of optimal transportation problem is the existence of functional inequalities like isoperimetric inequalities. Applications of such inequalities led us [505] to new and robust principles for the dimensioning of mobile networks operated under the OFDMA protocol.

We were also interested in the performance evaluation of some real times systems. In such systems, the evolution after each time depends on the whole past of the system. It is well known in Markov theory, that history can be taken into account by increasing the dimension (in the algebraic sense) of the state space. In the system we studied, this history was put in an infinite dimensional space, namely we worked on the space of tempered distributions. Using abstract results developed by A.S. Üstünel a few years ago, we were the first to find some limit theorems for high traffic regime [299, 300] for the so-called *Earliest Deadline First* discipline.

Another tool for stochastic modeling is made by random linear operators. Since the meeting between Montgomery and Dison in 1972, it is clear that there should exist deep connexions between number theory and random matrices. In this spirit, in [276], we gave a probabilistic proof of some formulas yielding $\zeta(2n)$. This is based on a representation of $\zeta(2n)$ as the Mellin transform of some Cauchy-related random variables. We also gave a generalization of this result to some $L$ functions related to some Dirichlet characters. In [277], we showed that $\det(Id - u)$ can be decomposed as a product of independent random variables for $u$ chosen according to the Haar measure on the unitary group. This implies an elementary proof of a central limit theorem conjectured in the eighties. These results were then extended to some Lie groups and some perturbations of the Haar measure, see [278]. It must be noted that these approaches can be applied to make explicit some computations for MIMO systems.

### 2.2.2 Discrete Mathematics, Communication, Information

**Faculty :** P.-Y. Angrand, D. Auger, **I. Charon, G. Cohen**, L. Denœud-Belkacem, J.-P. Flori, **O. Hudry**, B. Kindarji, **A. Lobstein, D. Madore, H. Randriambololona, J. Sakarovitch**, R. de Souza, G. Zémor.

**Projects :** *Projet structurant* : COOPT

- European grant VIPBOB

#### Algebraic Geometry, Number Theory and Cryptography

One research direction is the approach to problems of arithmetic nature (transcendence, Diophantine equations) by geometric methods (algebraic geometry, Arakelov geometry [337], Hermitian lattices). But of equal importance is also the application of these same geometric methods to concrete problems in combinatorics, coding theory, cryptography, analog and digital modulations, quantum information theory, etc.

With F. Castro, I. Rubio, O. Moreno, and H.F. Mattson Jr, we gave new proofs and then improvements, of some results about the number of solutions of systems of polynomial equations over finite fields [361]. We then gave applications of these new results to problems in coding theory.

With J.J. Boutros and F. Kharrat ([358]), we studied the quantification problem for the state space of a MIMO channel. In particular we compared results obtained from models based on various quantification methods, some of which naive, some others sophisticated, relying on the very differential geometric properties of the natural structure of Hermitian symmetric space carried by the space state of the channel.

Again with J.J. Boutros, we constructed a space-time code for $2 \times 2$ MIMO channels that is optimal both for maximum likelihood decoding and for iterative decoding ([359]). This construction was made possible by the use of objects from various branches of mathematics: matrix groups, quadratic forms, algebraic number theory, generalized quaternions.

In public-key cryptography, we began to explore the possibilities of finding cryptosystem not relying on the hardness of the discrete logarithm or the factorization, and if possible, efficient. That is why we are studying the potentialities of objects stemming from algebraic geometry such as algebraic tori, semi-abelian varieties, cubic hypersurfaces, in existing cryptosystems (especially on elliptic or hyperelliptic curves, e.g., pairings). We also study links with coding theory (e.g. toric codes) and information theory (secret sharing) and the possibility of applying combinatorial game theory to cryptographic protocols (so as to formalize them).

**Combinatorics and Optimization**

The external co-authors are I. Honkala (University of Turku, Finland), Y. Ben-Haim (University of Tel-Aviv, Israel), S. Gravier, M. Mollard and J. Moncel (researchers in Grenoble), A. Guénoche (CNRS, Marseille).

Once we realize that any technological system will eventually suffer errors or failures, it is necessary to develop tools to handle such events. For instance, in a multiprocessor architecture, we may want locate the malfunctioning processors. The so-called identifying codes in graphs are one of the best possible way to achieve this goal. Hence, we studied the properties of these codes, as well as the ones of the graphs admitting identifying codes, called twin-free graphs. We also studied two other kinds of codes, whose definitions are close to the one of identifying code: the locating-dominating codes and the discriminating codes in bipartite graphs. This is, in particular, the subject of D. Auger's PhD thesis [271, 272, 273]. Different aspects were considered: structural properties, study of special graphs, complexity issues, or search of exact algorithms [281, 282, 283, 286, 287, 295, 296].

Another direction of research deals with problems of distance between partitions, as well as the application of partitioning methods to bioinformatics. These topics were partly the subject of the PhD thesis of L. Denœud-Belgacem [284, 285, 289, 290]. Note that the "Prix Simon Régnier" was awarded to L. Denœud-Belgacem by the "Société francophone de classification" for her work in this field in 2007. Last, we would like to mention the continuation of our study of combinatorial properties of tournaments and of combinatorial optimization [288, 291, 315, 316].

**Information Theory**

The main recent activity in the field is related to the extension of the European project VIPBOB (Virtual Pin Based on Biometrics). The new challenge, from the cryptographic point of view, is that digitalized biometric data cannot be reproduced exactly every time it is extracted from a physical person. This is a situation that can't be covered by classical authentication schemes that do not distinguish between "almost correct" and "completely wrong". Therefore, if biometric data is to replace more traditional passwords, existing protocols must be modified in a way that will tolerate slightly erroneous submissions. This is a situation where the theory of error-correcting codes proved to be relevant. A protocol of Juels and Wattenberg was the basis for the European project VIPBOB in which the Telecom ParisTech team MIC$^2$ took an essential part.

This application of coding theory to biometrical identification is potent. However, a number of questions needed to be addressed. In practice, the distribution of biometric traits is far from uniform and the scheme is liable to leak undesirable partial knowledge to an unauthorized third party. It was thus desirable to have a protocol for which zero information leakage to potential eavesdroppers is guaranteed. As was put forward in the VIPBOB project, the information leakage problem can be interpreted as a wire-tap channel problem. Through this modeling we obtained precise measures of information leakage and proposed more robust schemes in [362].

Then, we explored the possible applications of this approach to devise a biometric identification technique based on the iris, in the framework of a contract with SAGEM; the idea was to use a product of two simple codes, equipped with a fast decoding algorithm [279].

Bruno Kindarji has begun a PhD CIFRE on biometric identification, co-supervised by H. Chabanne (SAGEM) and our team (Cohen and Zémor).

#### Automata Theory

The activity in this domain is conducted by J. Sakarovitch, his PhD students (R. de Souza, P.-Y. Angrand) and several external collaborators, mainly S. Lombardy. It may be described under four themes: synthesis, research, non-standard numeration systems, and construction of software for handling finite automata.

The concepts, methods et results of automata theory pervade the whole field of computer science. The English edition [381], published by Cambridge University Press, of the monograph (in french) published in 2003 aims at showing both the unity of the subject and its wide scope in a pedagogical approach.

In research, the systematic use of coverings revealed a structural approach to automata that proved to be very fruitful. We showed, with M.-P. Béal and S. Lombardy in [356], that the equivalence of automata with multiplicity can be expressed in terms of conjugacy; a deep result, which can be applied to the theory of automatic structures and to the axiomatisation of $N$-rational series. With R. de Souza, we rewrote a new theory for finite valued transducers, based on the notion of lexicographic covering. With S. Akiyama and Ch. Frougny, we showed how the introduction of numeration systems in rational base allows to make progress in the problem of the repartition of the powers of rationals modulo 1 ([267]). Some other works complete the applications of finite automata to non-standard numeration systems ([357, 270]).

As for the software activity, Vaucanson, a C++ platform for computing with weighted automata and transducers, is written in collaboration with a team from EPITA and is under development. It also gaves rise to a cooperation with the National Taiwan University. Along with the platform, we developed an XML format for finite automata. Finally, Vaucanson-G, a LaTeX package for drawing automata and graphs, co-written with S. Lombardy, is now publicly available from the CTAN servers.

### 2.2.3 Quantum Information

**Faculty:** **R. Alléaume, E. Diamanti,** A. Leverrier, **D. Markham**, P. Bellot, G. Cohen R. Medeiros, D. Elkouss, M. Dianati, S. De Crescenzo, M. Nicoletti, R. Guerra, P. Jouguet, A. Bocquet, G. Zémor.

**Projects :** *Projet structurant :* TRAQUE

- SECOQC, European Grant FP6, Trust & Security, (04/04 – 10/08).
- PROSPIQ, Projet ANR PNANO, (01/07–06/10).
- SEQURE, Projet ANR SeSUR, (01/08 – 12/10).
- COCQ, Projet ANR Domaines Emergents, (01/09 – 10/11).

Main Collaborators: Groupe de Philippe Grangier (Institut d'Optique), groupe de Nicolas Gisin (GAP Optique Genève), Austrian Research Center (Vienne, Autriche), groupe de Norbert Lütkenhaus (Institute for Quantum Computing,Waterloo, Canada), Institut Mathématique de Bordeaux (Gilles Zémor), Joseph Boutros (Texas AM Univ, Qatar), groupe de Nicolas Cerf (Université Libre de Bruxelles).

**Quantum Networks**

We developed an architecture and protocols specifically adapted for the distribution of secret keys over large scale networks. They were tested and validated within the European consortium SECOQC: The first live demonstration of a working quantum key distribution (QKD) network took place in Vienna in the framework of the SECOQC Demonstration and International Conference [335, 365, 369, 304]. Eight QKD-links were combined in a novel quantum-back-bone network physically deployed within a typical metropolitan area network to connect different company sites from SIEMENS Austria. Typical applications for QKD, to secure data traffic from telephony and video conferencing, were included in the demonstration.

We also studied quantum networks from a fundamental point of view, looking at security within the model of "Trusted Repeater Nodes" and its extension to the case of corrupted nodes [339], a crucial factor in any realistic "telecom" approach of quantum key distribution networks. We established a new methodology for the optimization of topologies for future quantum networks, and obtained novel results improving the design of experimental systems and facilitating economic planning of the deployment of large scale quantum networks [268].

We proposed a new definition for quasi-trusted relays from which we developed a 3-party quasi-trusted model called Quantum Quasi-Trusted Bridge model that allows to securely distribute shared keys over arbitrarily long distances without invoking entanglement swapping and entanglement purification. We developed a model of stochastic routing for quantum networks and proved its validity using percolation theory. It is dedicated to large-scale quantum networks where some of the nodes can be secretly eavesdropped. We showed that under computable conditions, large-scale quantum networks can protect the transmission of data with a extremely high probability. Focusing on Cascade algorithm, a major step of the quantum key distillation algorithm (BB84), we showed that the mathematical optimality may not mean practical efficiency because of the design of computers and their processors. The result is a new and efficient implementation of BB84. This software allows the encoding of data transmission via Vernam code or AES. It also allows the transmission of video and sound over the quantum link.

**Quantum Key Distribution and Quantum Information Theory**

Work on quantum key distribution has been carried out within the framework of European project SECOQC, and ANR projects SEQURE and PROSPIQ, and has been conducted along two principle axes: the establishment of demonstrations in optical fiber and/or in free space, and the theoretical study of new high performance protocols along with the formal proofs of their security. Leading an international effort in this direction, we studied the role of quantum key distribution in the broader landscape of current cryptography, as discussed in detail in the "SECOQC Crypto White Paper", edited by R. Alléaume. This White Paper is the outcome on a thorough consultation and discussion among the participants of the European project SECOQC. This paper is a review article that attempts to position Quantum Key Distribution (QKD) in terms of cryptographic applications. A detailed comparison of QKD with the solutions currently in use to solve the key distribution problem, based on classical cryptography, is provided. We also detail how the work on QKD networks lead within SECOQC will allow the deployment of long-distance secure communication infrastructures based on quantum cryptography. The purpose of the White Paper is finally to promote closer collaboration between classical and quantum cryptographers. We believe that very fruitful research, involving both communities, could emerge in the future years and try to sketch what may be the next challenges in this direction.

Experimental aspects of research are led by collaboration with the Institut d'Optique. The arrival of E. Diamanti, previously at the Institut d'Optique, to our team allows us to capitalize on a well respected and known expertise in the field, whether for continuous variables [308, 309, 323], or discrete variables [341, 303]. In particular, E. Diamanti was responsible for the implementation of an all-fiber continuous variables quantum key distribution system for the European project SECOQC [335].

On the theoretical side, our team proposed new techniques for error correction for both discrete [366] and continuous [320] variables. A. Leverrier co-invented a new continuous variable key distribution protocol, which improves performance of real systems [322]. In addition, the proof of security for these protocols provided new results of fundamental interest to quantum information.

Finally, we progressively developed our theoretical activity in quantum information, most significantly in the direction of quantum codes within the project ANR COCQ. In collaboration with the Universidade Federal de Campina Grande, Brazil, we extended the notion of zero-error capacity to the quantum framework [332, 368], giving a necessary and sufficient for non-null capacity, and reformulating the determination of the capacity in graph theoretical terms. The arrival of D. Markham to our team allows us to engage in the study of fundamental problems linking entanglement and quantum computing [269, 379, 334], for example by the conceptually useful unification of quantum error correction codes, secret sharing and one-way quantum computation notably via the "graph states" and the stabilizer formalism [329, 314, 330].

#### Industrial Development

The enterprise SeQureNet was created in February 2008. It is a "spin-off" from the research activities initiated within Telecom ParisTech/INFRES in the framework of the European FP6 project SECOQC and is aimed at the industrial development of networks for quantum key distribution. The enterprise was launched based on the success of winning two prizes in the national competition for "concours national de création d'entreprises de technologies innovantes" organized by OSEO and MNRT, first in 2007, and then in 2008 (in the categories "émergence" and "création-développement" respectively). Part of the generated intellectual property generated by our research in quantum information is already linked with industrial development via SeQureNet. A software "SeQure Phone" allowing for secure communication between a smartphone and a server over a quantum network has been registered and the protocol [322] has been filed with the patent office. In addition, the network protocols we specified, having been given the opportunity to develop in the European SECOQC project, are now en route to becoming the European standards which permit the integration of quantum key distribution into standard telecommunications networks. Our team actively participated in work on standardization, run under ETSI, within the "QKD Specification Group" which we co-founded in 2008.

### 2.2.4 Combinatorial Optimization for Optical Networks Design and Traffic Engineering

Within the Institut Telecom, our research in the domain of optical networks is organized around the ETTON (Ethernet Technologies and Transparent Optical Networks) collaborative project. In terms of tools, both exact techniques (Branch and Bound, ILP formulation) and approximate techniques (heuristics, metaheuristics) are requires to address a vast class of problems.

**Research team : M. Gagnaire**, N. Puech, E. Doumith, S Al Zahr, R. Aoun, M. Youssef, C. Cardenas, A. Morea, A. Pichot.

**Projects:** *Projet structurant :* ETTON

- DICONET: "*Dynamic Impairment Constraint Networking for Transparent Mesh Optical Networks*", STREP European research project, (01/08–06/10).

- BONE: "*Building the future Optical Network in Europe*", European Network of Excellence (NoE) on optical communications and networking; (01/08–12/10).
- e-Photon ONE: "*Optical Networks in Europe*", European Network of Excellence (NoE) on optical communications and networks; (03/06–02/08).
- Research contract with Orange-labs in Lannion "*Access networks: architecture and traffic modeling*"; (09/05–05/07).
- Sebastian 2: "*Resource virtualization and pricing strategies for collaborative remote digital image processing*", research project in collaboration several parisian animation studios, (01/08–12/09).
- Carriocas, sub-project within the National Systematic research project: (10/06–09/09).

**Traffic Aggregation in Multilayer Networks**

In 2002, we introduced the concept of *Scheduled Lightpath Demand* (SLD). Unlike a *Random Lightpath Demand* (RLD), an SLD is dynamic and deterministic. It is characterized by a 5-tuple made of the source and destination nodes, the bandwidth capacity expressed in number of optical channels, the date of activation, and life duration of the connection. We proposed the very first Routing and Wavelength Assignment (RWA) algorithms exploiting time-space correlation between SLDs (PhD of J. Kuri). These algorithms enable to reduce considerably the cost of optical cross-connects (OXC) in the network. Since 2002, numerous papers in international conferences and journals proposed extensions or variations of our original approach. We extended the SLD concept to traffic demands with fractional wavelength capacity (PhD of E. Doumith). Such traffic requests are designated by *Scheduled Electrical Demands* (SED). By extension, we have also introduced the terms of PED (*Permanent Electrical Demand*) and RED (*Random Electrical Demand*). We proposed the first RWA algorithms including shared-path protection under SLD/SED traffic (PhD of M. Koubaa). We proposed an original traffic characterization relying on a decomposition of real traffic traces into a set of PLDs/PEDs, SLDs/SEDs and RLDs/REDs (PhD of E. Doumith). More recently, we focused our activities on multi-layer traffic grooming. Two contexts were considered: the encapsulation of electrical connections (typically MPLS LSPs) into lightpaths (PhD of E. Doumith) and the logical aggregation of lightpaths into wavebands (PhD of J. Kuri) [305], [312]. Our expertise in the field of grooming has motivated the writing of a chapter in a collaborative book published by Springer-USA in 2008 [375].

**Impairment-Aware Routing and Wavelength Assignment (IA-RWA)**

Within the National RYTHME project, we developed one of the very first RWA algorithms taking into account Quality of Transmission (QoT) also known as *Impairment-Aware RWA* (IA-RWA). The principal objective was to consider in the context of PLDs, the main factors degrading QoT, namely chromatic dispersion (CD), optical signal to noise ratio (OSNR), non-linear phase ($\Phi_{NL}$) and modal dispersion (PMD). We proposed a new algorithm called LERP (*Lightpath Establishment with Regenerator Placement*) aiming to judiciously place electrical regenerators (ER) when bit error rate (BER) goes beyond a certain admissibility threshold [311] (PhD of S. Al Zahr). Minimizing the global amount of regenerators is a CAPEX-oriented objective. Carriers also should like in parallel to favor a concentration of ERs in the network for OPEX purposes [367]. In the context of the European DICONET project, we developed a new algorithm called COLERP (*Cross-Optimization LERP*). COLERP aims at a triple objective: minimize rejection ratio, global number of ERs, and number of regeneration sites [353] (PhD of M. Youssef). Our coming studies deal with two topics: hard failures monitor's placement strategies and soft-failures monitor's placement strategies. If a few recent papers deal with hard failures, soft-failures related to aging of devices and systems remain a very open field of investigation.

#### Virtualization and Pricing Strategies in Cloud Computing

Grid Service Providers (GSP) are typically interfaced on one hand with clients generating job requests and on the other hand with resources (computing facilities, storage devices, networking facilities) providers. Considering a fluctuation in resources availability, our aim is to determine on which computers, storage devices and networking facilities a set of jobs can be satisfied at the lowest cost. In the context of the Carriocas national research project, we proposed a first economic model based on an Integer-Linear-Programming formulation aiming at maximizing the gain of the GSP [354]. Our approach is advantageous compared to an on-the-fly approach both for the clients (lower rejection ratio) and for the GSP (increased gain). We extended this analysis to the concept of sliding window in which a client may wish the processing of his job. The wider this window, the lower the cost for the client, the more efficient resources' utilization, and the higher the number of accepted jobs. In order to consider realistic network scenarios, we also proposed a meta-heuristics to deal with this same problem [355] (PhD of R. Aoun). Other investigations were carried out in Grid Computing dealing with architecture and protocol aspects (PhD of A. Pichot) and on the application of Flow Aware Networking (FAN) developed in Orange Labs for Grid sessions admission control in IP networks [360] (PhD of C. Cardenas). We shall soon collaborate with Essex University under BONE NoE in order to consider the delays required for network resources establishment.

#### Control Plane for Hybrid Optical-Wireless Access Systems

In collaboration with Prof. Mario Pickavet, we proposed an original analytical model of the IEEE 802.3.ah EPON MAC protocol. This model takes into account the MPCP signalling protocol and the IPACT dynamic bandwidth allocation mechanism [318], [319]. In the context of a collaboration with Orange-Labs, we proposed a passive WDM metro-access architecture including AWG routers and colorless Optical Network Units. We designed an original control plane applicable to this architecture in order to provide dynamic optical bandwidth capacity to multiple WDM-PONs [310]. Our coming studies are extending these studies to the federation of WDM-PONs and Next Generation wireless base-stations thanks to Radio-over-Fiber techniques.

## 2.3 References

Below is the full list of articles published, since January 2005, in international journals by current members of the team (thus, these also includes a few publications that where not counted in the summary table of page 30). As regard articles in proceedings, only the selected articles which are cited in the text appear below. The full list of publications of the team is available at the following URL

`http://www.infres.enst.fr/wpmufr/mic2/publications/`

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# Chapter 3

# Networks, Mobility, Security (RMS)

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ALESSANDRIA Eugénio (1 months), BACHELIER Stéphane (18 months), BENCHAIB Yacine (25 months), BIANZINO Aruna (2 months),DJARALLAH Nabil (2 months), ELRHARBI Simon (21 months), KIENNERT Christophe (12 months), LAURIER Philippe (27 months),LAVINAL Emmanuel (14 months), MARIE Estelle (5 months), MENDOUGA Laure (10 months), ODIC Xavier Steve (18 months), RAJU Pusapati (1 months), SOTTILE Elisa (7 months), TESTA Claudio (4 months), VALENTI Silvio (6 months), VEGLIA Paolo (6 months), ALCOBER Jesus (12 months), RÄTY Tomi (7 months), SUNGHYUN Kim (13 months).

| | |
|---|---|
| Faculty [IT, CNRS] | [14, 0] |
| PhD students | 30.9 |
| Post-docs, engineers and sabbaticals | 5.3 |
| Defended PhD theses | 37 |
| Defended HDR | 3 |
| Journal papers | 45 |
| Papers in conference proceedings | 273 |
| Chapters and books | 19 |
| Patents and sofware | 16 |
| Grants [public, private, european] (k€) | [4246, 2301, 2349] |

## 3.1 Scientific Environment, Positioning and Objectives

The NMS team covers a broad, consistent thematic field, as shown in the first part of this introduction. As networks are at the heart of the Télécom ParisTech scientific and technological field, we have chosen to cover a large number of topics that we consider to be strategic for enabling the expected development of networks and services. The second part of the introduction provides a reminder of the high level of involvement of our team in national and international research initiatives and organizations as well as its numerous collaborations with the industrial sector.

Services are becoming personalised, ubiquitous and agnostic in relation to the technologies and networks used to gain access to them. These personalised services adapt themselves dynamically to the context and the location. We hold that major flexibility will be introduced through the concept of having a composition of services where various actors propose components used to dynamically create new services that fulfil specific needs. These developments require major changes in services' architectures. Our research strategy is focused in architectural modelling, enabling the problem to be understood as a whole, and on innovative fundamental principles of future architectures. In particular, the team validated these principles in collaboration with various network and services operators. Moreover, service overlays, particularly in peer-to-peer (P2P) mode, are continually being deployed in order to support the development of services and particularly the distribution of content. Our contributions in this field relate to the design and analysis of P2P applications, work based on an innovative methodology that we pioneered. The relevant scientific contributions are presented in section 3.2.1.

Services are becoming mobile (a concept which largely goes beyond the mobility of users and terminals that we currently have); we will be able to cross technological frontiers and boundaries between administrative domains (different operators and service providers), and change terminals without the communication we have in progress being affected. All services are becoming mobile, and therefore the capacity needs are exploding. Within this context, the team has focused on two groups of topics: firstly the planning of new-generation wireless networks, cognitive

radio and scheduling at the radio interface (topics considered to be critical for optimal use of the spectrum) and secondly the mechanisms enabling seamless mobility, particularly across technological frontiers and administrative boundaries (an obstacle that limits service offers like the ones described above). Our contributions in this field are presented in section 3.2.2.

Peripheral to infrastructure networks and particularly to the access networks referred to above, we find devices (residential gateways, terminals, etc.) which increasingly have radio interfaces and functionality enabling opportunistic creation of self-organized networks. These networks can fulfil specific needs that change greatly over time. The generic concept of self-organised networks is not new, but its implementation in specific contexts (e.g. vehicle networks) has opened the door to a large number of applications and raised new scientific and technological problems. At the same time, new concepts such as wireless sensor and actuators networks (WSANs), new-generation RFID and the Internet of things, will enable the real and the digital worlds to be brought closer together, thus facilitating new services which will change our lifestyles. This is a wide-ranging topic; on the one hand we have focused on certain algorithms and protocols enabling fundamental issues to be resolved (efficient and fair sharing of resources, time synchronisation) and on the other hand we proposed innovative architectures for wireless sensor networks (including one pioneering contribution usually cited), for vehicle networks and for mesh networks. Our contributions to self-organised networks are presented in section 3.2.3.

The architecture of IP networks (including the Internet) will have to change in order to integrate the concepts outlined above, and in order to integrate new network paradigms facilitating the offering of services like the ones described. In particular, the team focused on inter-domain routing, an issue recognised as being one of the main obstacles to networks development. Indeed, present Internet inter-domain routing neither allows for guaranteeing QoS or deploying efficient traffic engineering approaches. Moreover, advanced services, such as IP Virtual Private Networks, are seldom interconnected due to the complexity of existing solutions. We present our contribution to these topics in section 3.2.4. Moreover, the team is also involved in initiatives dealing with more radical changes in Internet architecture.

Security is an ever-present, fundamental topic involved in all of the themes presented above, and future networks and systems will have to include security right from their design stage onwards. Within a dynamic context like the one described above, the development of numerous usages requires the establishment of solutions enabling users' trust to be developed whilst at the same time devoting attention to respecting privacy. The central socio-economic role of networks makes studies concerning infrastructure safety a necessity. Our results regarding these topics are outlined in section 3.2.5.

The team is greatly involved in national and international collaborative research projects (financed by the FP7, the ANR and competitiveness clusters). It was the initiator of the PF6's European Network of Excellence (NoE), Euro-NGI and of its successor in the FP7: Euro-NF. It has chaired this NoE's Steering Committee since it was created. The Steering Committee is, in particular responsible for co-ordinating all research activities of the NoE. Moreover, by way of an example, during this period the team participated in several European projects (NapaWine, SEINIT, CI2RCO, IRRIIS, Seserec, TIGER and Bugyo) and in the RNRT and ANR Actrice, Diaforus, Georacing, R2M, TRAFFIC, IROISE, Resodo, T2TIT, ESTER, and OSCAR projects, among others. The team is involved in the System@tic (trust platform) and CapDigital (wireless high-speed Internet) competitiveness clusters.

The team is also involved in numerous bilateral research contracts with industrials, and particularly with Orange, SFR, Alcatel-Lucent and Thales. It maintains close links with various international laboratories, including Turin Polytechnic, Milan Polytechnic, the University of Waterloo, Imperial College, Hubert Curien Partnerships, and STIC Asia Partnerships. The group participates in numerous projects.

In 2009, one of its members chaired the Experts Committee of the ANR's VERSO programme. Within the Telecom Institute, it is greatly involved in the Networks of the Future lab, and several of its members are part of its Experts Committee. Moreover, the team regularly responds to

requests for expertise from various French and European institutions. As far as innovation is concerned, members of the team were either the founders of, or are greatly involved in, innovative enterprises dealing with technologies that have resulted directly from research work within the team.

## 3.2 Main Results

### 3.2.1 Services Architecture and Applications Services

**Faculty** Dario Rossi, Noëmie Simoni.

The development of new services and usages makes it necessary to rethink how services and content are made available. The major changes required for a dynamic composition of heterogeneous services, provided by multiple actors, in a way that is transparent to the user, may be summarised as follows:

- Shifting from a vertical architecture (in silos) to a horizontal architecture (that is integrated).
- Shifting from a client-server architecture (strong coupling) to a service-oriented architecture (loose coupling).
- Shifting from a centralised architecture to a distributed architecture (P2P).
- Shifting from a static architecture to a dynamic, flexible architecture.

The joint design of networks and applications services is required to ensure the end-to-end continuity of QoS, guaranteeing full integration. Personalisation of the user's workflow, which is now central to the solution, brings about a trans-organisational context where session mobility needs to be managed.

There are several approaches for achieving the simplification, reuse and loose coupling of the various services, above and beyond Web 2.0/3.0, which was the first to emphasise the sharing of knowledge and social networks. The next stage, represented by Service Oriented Architecture (SOA), and Software as a Service (SaaS), is defining a paradigm for the organisation and use of the distributed capacities of services platforms: our initial research orientation is aiming to go beyond the limits of these approaches.

An important aspect of the Darwinian evolution of the Internet has undoubtedly been the introduction of the "peer to peer" (P2P) paradigm. In light of the impact of P2P applications, we were interested in two major issues: analysis of the traffic structure that they generate (in order to facilitate handling them), and their mechanisms for interaction with the network (enabling a global optimisation of resources). We have come up with innovative methods for traffic classification (the usefulness of which extends well beyond the framework of this study) which have enabled us to understand certain operating principles of the main P2P applications as well as their mechanisms for interaction with the network. These results are now recognised by the scientific community in light of their usefulness in joint services/networks design, especially through integrating self-adaptation mechanisms (work in progress within the team).

#### Main contributions

**Development of applications services**

Here, our work relates both to the design and analysis of P2P applications. Of the major results, we can cite the analysis of Skype congestion control mechanisms [408] or its signalling [600, 383], as well as the characterisation of its users [385], or of the black-out which caused an outage of the Skype network lasting three days in a row and which created a firestorm of messages on the Internet [430]. Other aspects taken into account concern the study devoted to

VoIP service quality [407], and the impact of P2P-TV applications on the network [395, 538, 432, 431], which depends on their level of knowledge of the underlying.

Analysis of these applications was made possible by the development of reliable, sophisticated techniques for the classification of Internet traffic, based on the recognition of the applications that generated the flows of information. To do this, we proposed an analysis method based on the similarities that exist between the dynamics of human communications and exchanges of digital data carried out by Internet applications [409, 433, 450, 438, 412, 439]. Two orientations were considered: the first was the similarities of the verbal aspect of communication with a new class of classification technique: "Stochastic Packet Inspection" (SPI) [438], a statistical extension of DPI. It should be noted that the germ of this idea is described in [409, 433, 450], which is currently considered to be the state of the art for Skype classification. The second orientation relates to the behavioural exchanges of applications, whilst completely ignoring the packet content and only considering the behaviour of the traffic [412, 439]: here, the similarity is more with the dynamics involved in human interactions.

**Development of service architectures**

The NMS team has fully contributed to the integration and joint design of networks and services. It is thanks to a unified approach and an architectural modelling of NGNs (Next Generation Networks) and of this new generation of services that converging, dynamic and flexible solutions for networks and services have been proposed. The main objective is for the whole system to be at the user's service, unlike other approaches, where the user must bend to the various connections constraints (Network Centric) or processing constraints (Application Centric). One of the main results is the proposing of an information model for managing a user-centric session (a time-based connection with the system). In other words, this is a session by a user wanting to establish his workflow dynamically depending on the services that his environment may offer during all his travels. To achieve this, in [454, 593, 394, 624, 539, 623, 619] we propose a structuring of this new personalised service landscape, which is trans-organisational and based on the dynamic service composition, subject to QoS constraints within a generalised mobility environment. But a service is neither an application nor a transaction, and still less a system. As we noted above, the SOA and SaaS approaches have enabled development, but they are not sufficient for ensuring the dynamic nature and the integration of the service and networks. This is why we introduced self-management through the management of communities of interest and management of the QoS in terms of each of the service components. The global organisation is based on the ubiquitous nature and sharing of the service components. What is original about this is that it steps outside of the client-server model by proposing the implementation of the user's service logic (workflow) in the same mobile session, based on the sharing of service components.

### 3.2.2 Wireless Networks and Mobility

**Faculty** Nadia Boukhatem, Marceau Coupechoux, Philippe Godlewski, Daniel Kofman, Houda Labiod, Philippe Martins.

Support for the development of the services previously described in this document in particular requires two major developments: firstly, a major increase in the capacity of access networks and, secondly, advanced management of mobility.

Over recent years, cellular radio interfaces have experienced rapid development. Beyond increases in speeds, in particular this has been characterised by new packet mode optimisation mechanisms, the coexistence of several technologies, greater equipment agility in terms of frequencies, and the use of OFDMA for the physical layer. Dimensioning and capacity calculation methods have been greatly modified because of the characteristics of the physical layer, and services and users, are changing. Radio access scheduling and protocols must be adapted to the constraints of new services. Making access transparent to the user requires the development of advanced inter-technologies handover algorithms. Lastly, the promises of radio software are forcing us to rethink spectrum management methods.

### Main contributions

#### Capacity and dimensioning of wireless networks

The group is interested in the dimensioning and planning of wireless networks. This requires evaluation, firstly, of coverage and, secondly, of the capacities of these networks. These two aspects are linked by the spatial distribution of the Signal-to-Interference+Noise Ratio (SINR). The coverage ratio is in fact defined by the probability of exceeding the SINR. The cellular capacity, on the other hand, is an increasing function of the SINR. Within the context of CDMA networks, and working in collaboration with Orange, we expressed (the results are presented in [413]) the spatial distribution of the SINR and the probability of exceeding it, taking masking and attenuation effects into account. Within the context of OFDMA networks and in collaboration with Alcatel-Lucent, we compared different frequency reuse schemas (the results are presented in [529]). In [504], we propose an approximation of the SINR when the cells are distributed according to a spatial Poisson process.

The group proposed an innovative approach, based on stochastic geometry, for planning metropolitan wireless networks. This approach enables simple engineering rules to be obtained in spite of the complexity of the problem [426]. The work was carried out in collaboration with the ENS within the context of the Iroise RNRT project.

In collaboration with Alcatel-Lucent and UPMC/LIP6, we developed dimensioning algorithms for WiMAX networks based on the Markov chains theory and taking into account the various types of traffic (best effort, voice, etc.) and different types of radio channels [406].

#### Scheduling and radio access protocols

The group is interested in scheduling algorithms and in radio access protocols.

Opportunistic scheduling dynamically considers the variable capacity of the radio channels of the various users sharing the radio resources of a given cell in order to obtain a good compromise between the optimisation of these resources and the fairness between users. We proposed and evaluated a new opportunistic scheduling mechanism which improves the performance of the very popular WFQ scheduler (used in wired links) whilst maintaining fundamental properties like fairness. Some of the scheduler's properties are demonstrated analytically [426]. The work was financed by the Iroise RNRT project.

OFDMA scheduling consists on allocating groups of sub-carriers of the band to the cell's users. We propose an algorithm [574] that maximises the cell's capacity whilst at the same time ensuring the users' individual througput. To guarantee real-time traffic maximum delays and to maximise non real-time traffic throughput whilst at the same time ensuring proportional fairness between both of them, two algorithms, extensions of WFS (Wireless Fair Service) for OFDMA, are proposed by the team in [579]. In the field of random access, together with the BUPT (Beijing, China), we proposed a new algorithm for WiMAX in [411]. The group provided a consulting service to the European Space Agency for standardisation - CCSDS.

#### Cognitive radio and dynamic access to the spectrum

The frequency spectrum is considered to be poorly used: certain bands are locally and temporarily congested while others are under-used. Current software radio techniques will soon enable radio interfaces to be quickly and dynamically reconfigured across broad bands of the spectrum. These technologies greatly modify the management algorithms for the radio resource. The group is giving consideration to these questions and is proposing solutions in the TEROPP (inter-Carnot) and URC (SYSTEMATIC competitiveness cluster) projects, e.g. in [498].

#### Mobility management and handover algorithms

The group has developed expertise in the field of multi-technology handovers. Cross-layer optimisation strategies have been proposed for the data handover in multi-technology EGPRS and WLAN networks (in the ANAIS RNRT project) [502] on the one hand, and WiMAX and 3G LTE (with Orange) [583] on the other hand. We have also proposed solutions based on extensions to the SIP protocol, enabling roaming to be managed at the application level [451].

A new anchoring points selection approach within the IPv6 Mobile architecture, which offers good performances within a broader context compared to existing solutions adapted solely to specific mobility cases, was proposed and evaluated [440]. This work was carried out in collaboration with Orange Labs under the framework of a bilateral project.

Studies on the dynamic selection of interfaces, considering various attributes such as the characteristics of the interfaces, applications' needs, and user preferences, were carried out. In particular, MADM (Multiple Attribute Decision Making) methods applied to interface selection were evaluated [640], and a new method which eliminates classification anomalies was proposed. The group is also interested in the issues raised by the multi-home nature of mobile terminals and the possibility of having these terminals communicate simultaneously with two different radio access systems. Within this context, we are working on the impact of multi-homing on mobility management protocols (MIPv6 and MIPv4), and a mechanism which extends the mCoA (multiple Care of Address) solution was proposed. SCTP's multi-homing functionality was exploited to develop inter-system handover mechanisms [463]. Lastly, we use games theory as a tool for modelling multi-interface terminals.

**Analysis of the protocols on the radio interface**

The VIGIE software (GSM/GPRS) enabling protocols on the radio interface to be analysed, which was designed and developed in collaboration with Telecom Bretagne, formed the subject of an application to the APP in 2007. The group is now working in collaboration with SFR on new software (called "Metradip") for 3G/HSDPA systems. In addition to its interest for operators, such software constitutes a very valuable tool for teaching purposes.

### 3.2.3 Spontaneous Networks and Self-Organisation

**Faculty** Claude Chaudet, Marceau Coupechoux, Daniel Kofman, Houda Labiod, Jean Leneutre, Jean-Louis Rougier.

Peripheral to infrastructure networks, we are witnessing the generalised use of new network paradigms, often with self-organisation properties. Work in this field was originated by the research on packet radio networks carried out by DARPA from the 1970s onwards. In particular, reference may be made to multi-hop radio networks, for which several application classes have emerged over the last decade.

Recently, several specific applications, such as environmental monitoring and road safety and road traffic management applications have enabled the behaviour of these networks to be evaluated under real or realistic conditions. The experiments conducted have enabled several scientific challenges to be identified and have given impetus to themes such as wireless sensor networks, mesh networks, and vehicular networks.

Numerous scientific and technical issues remain and must be solved so that the deployment of spontaneous networks capable of arousing the interest of a critical mass of users can be deployed. Within this context, we have focused on the one hand on fundamental and generic issues (distributed location, clocks synchronisation, sharing of resources) and, on the other hand, on specific architectures (wireless sensor networks, vehicular networks, and radio mesh networks).

**Main contributions**

**Distributed location and clocks synchronisation**

In the context of self-organized networks, the NMS team has proposed several algorithms and protocols enabling the solving of fundamental issues required for ensuring good local functioning on which end-to-end protocols can rely on. In particular, contributions have been made (and are currently being published) on distributed location based on a low number of fixed points in the network.. Moreover, a scalable method for clocks synchronisation for ad-hoc nodes has been proposed in [491, 387].

**Sharing of resources**

The performance and overall behaviour of these networks is the result of a set of local behaviours and consequently they are difficult to characterise and influence from a global perspective. Ensuring a fair sharing of resources, for example, requires collaboration between transmitters in order to avoid having one group of terminals monopolising all of the available resources. Such a situation may be the outcome of unintentional behaviour, egotistical or intentional behaviour, or may be the result of an explicit attack on the network. The team is examining these three scenarios. While a purely algorithmic and protocol-based approach based on local measures enables unintentional unfair situations to be responded to [401], using games theory, particularly for defining the power control and resources allocation policy, enables egotistical behaviour to be discouraged [493, 388]. Furthermore, this work led to contributions relating to detection of, and protection against, the attacks referred to in the chapter within this report relating to safety.

The contributions outlined in the preceding paragraphs are generic. They do not presuppose either a particular network architecture, or a particular mobility for the nodes, nor do they presuppose a limit to their energy reserves. At the same time, NMS team has taken an interest in several types of particular distributed multi-hop networks, as follows.

**Wireless Sensors Networks**

Wireless Sensor Networks are generally low-capacity networks for which saving the energy of the various nodes is a key issue.

Often, their objective is to capture information and transmit it in multi-hop mode to a sink. Due to this architecture, the sensors close to the sink consume more energy; indeed they have to relay more packets. We proposed a heterogeneous sensors architecture (based on sets of sensors with different capacities and batteries), and we optimised it using modelling based on stochastic geometry, which enabled us to find structural properties ([396] quotation).

The team also proposed and optimised processes for waking up sensors and putting them into sleep mode based on cross-layer collaboration in order to optimise the disribution of energy expenditure within a network [604, 435].

**Mesh and hybrid networks**

Mesh networks and hybrid networks are based on the existence of a fixed infrastructure around which a multi-hop network is created. Under this framework, the team proposed improvements to the ad hoc OLSR routing protocol within the context [519], thus enabling the advent of routing circuits to be avoided when the Fisheye extension is used. In addition to routing, mesh networks formed the subject of several studies within the team, aimed at characterising their performance. Various combinatory problems were studied and led to the proposal of optimisation models [497].

**Vehicle networks**

Vehicular networks are characterised by their special mobility model and a distinction between inter-vehicle communication and communication between vehicles and an infrastructure. The speed of movements, as well as trajectory constraints, requires major changes in the addressing and routing policy. In particular, the NMS team proposed a routing protocol based on the trajectory, in which the next hop is chosen autonomously without control packets exchange with the neighbours [527, 528].

### 3.2.4 Core Networks

**Faculty** Nadia Boukhatem, Daniel Kofman, Jean-Louis Rougier.

Our work in this field is positioned in terms of the Internet architecture and the current development of operator networks towards an ”all-IP” approach. The objective is to enable an increase in the network’s capacity and control of it, whilst at the same time minimising costs. Consequently, our contributions relate to the following three aspects: architectural concepts for the optimisation of new-generation metropolitan and core networks, inter-domain routing, and traffic engineering.

### Main contributions

#### Network architecture

In order to reduce deployment and management costs, we are witnessing, on the one hand, a reduction in technology layers (for example with solutions like IP over WDM or IP over Ethernet Carrier Class) and, on the other hand, the seeking out of integrated management and control methods, or multi-layer methods, for the various technology layers. Within this context, we worked on the Bus-LSP concept [418], and we showed how it enables the deployment of cheaper transport architectures that are easier to manage. Solutions for the dimensioning of these networks were proposed [393]. This work was carried out in collaboration with Alcatel-Lucent.

We have also taken an interest in problems related to the diversity of IP signalling protocols deployed nowadays. Development costs, complexity, and management costs constitute the main issues in this regard. We defined unified signalling capable of supporting different signalling needs. In particular, we developed a generic transport protocol for signalling [480].

#### Traffic engineering

IP traffic engineering has experienced considerable development over the last few years. Nevertheless, existing techniques remain difficult to implement because they often require prior knowledge of the traffic, for example the traffic matrix, the characteristics of the flows to be transported, etc. And yet this information is sometimes difficult to measure and is often unpredictable. Consequently our research focused on defining efficient traffic engineering techniques, robust, with respect to unforeseen traffic changes, and which do not require any hypotheses regarding the traffic transported. In particular, we studied dynamic load sharing as a natural tool that fulfils these objectives. We proposed new load balancing methods, based on routing games (Wardrop Equilibrium) enabling to maximize the global utility of all of the transported elastic flows [422]. We also proposed load-sharing techniques based on cost functions measured through non-parametric regression [421, 603]. For example, these techniques enable the average timeframe required for all of the flows transported to be minimised without making any hypothesis about the traffic. In collaboration with Orange Labs, we have also taken an interest in using load sharing jointly with the cross-protect mechanism, enabling a QoS to be offered that is satisfactory for streaming and elastic flows, without any need for explicit identification of traffic classes [521].

#### Inter-domain routing

The services offered currently by operators are limited geographically (except for the Internet, which only offers a Best Effort Service), because they are only available within their networks. This situation is due firstly to the difficulties involved in defining a regulatory and economic framework where the operators will have real incentives to co-operate. Following on from that, the main reason is due to the absence of effcient inter-domain engineering mechanism. Under the framework of an ANR project, for connection oriented networks (e.g. MPLS/GMPLS), we proposed a network architecture based on the concept of an operators alliance, [392]. We defined inter-domain path selection mechanisms subject to multiple constraints; both economic and QoS-related ones [437, 611]. For the connectionless case , we used games theory in order to highlight the most effective inter-domain routing strategies. In particular, we demonstrated that it is possible to reduce congestion and reduce deflections on peering links, whilst at the same time protecting operators' independence (non-collaborative strategies) [613]. We also developed an SLA/SLS (Service Level Agreement/Specification) dynamic negotiation protocol for the provision of inter-domain QoS services. This protocol was designed to be flexible and configurable in order to overcome, on the one hand, the heterogeneity of solutions and deployed architectures for the provision of of QoS, and, on the other hand, the diversity of offered services [446].

### 3.2.5 Networks Security, Critical Infrastructure, Trust Objects

**Faculty** Pactrick Bellot, Artur Hecker, Houda Labiod, Jean Leneutre, Ahmed Serhrouchni, Pascal Urien.

The NMS group conducts research on the topic of security according to three orientations; networks security, critical infrastructures, and trust objects; these three themes do however address a single objective, which is the definition of secure networks, architectures and services. The security of the pervasive infrastructures which encompass wireless technologies, and ad hoc or mesh self-organised networks, is a major research orientation for removing technological obstacles for ambient radio networks. Likewise, the critical infrastructures study addressing issues such as auditing, data back-ups and automatic reconfiguration, is a key issue for the deployment of reliable information systems, which the emerging economy based on digital information transfers relies upon. Lastly, trust objects (or in other words IT platforms that can withstand attacks) integrated into the digital ecosystem and, more specifically, the Web, are the cornerstone of digital identity (or in other words strong authentication enabling access to diffuse radio services), guaranteeing the traceability of exchanges and limiting the risks of data being pirated. vspace0.5cm
**Main contributions**

**Network security**

The solutions studied for the Internet are aimed at traceability needs and requirements for optimising different resources (bandwidth, storage, processing). For telephony [442, 511, 689, 618, 434, 520, 516, 471, 484], we proposed a security solution based on the data channel, and independent of operators' infrastructures. This contribution enables users to check their consumption. Within the context of ad hoc mobile infrastructures and, more broadly speaking, autonomous networks [390, 465, 491, 493, 494], our work relates to defining trust models, as well as designing secure mechanisms and protocols adapted to these new stakes. We have defined a new global security architecture dedicated to MANETs networks and to hybrid mesh WLAN networks. In this latter case, we studied security-related problems within the most vulnerable part of such a system, namely the ad hoc subset within the operator context. The outcome of our work was the design of a comprehensive solution, while current solutions are generally only partial. In relation to heterogeneous mobile networks [557, 555], we designed a fast authentication protocol for the inter-domain transition, which combines 802.1x and PANA operations. We introduced access control based on trust, which enables access rights to be defined according to your past behaviour, recommendations and the reputations of those supplying recommendations, which offers the possibility of adapting access policies to the dynamic environment and of processing the interactions log on a long-term basis.

**Critical infrastructures**

[536, 534, 473, 558, 598, 535], started under the framework of the CELTIC BUGYO project, is being extended under the Deserec IST project and the Oscar RNRT project: modelling the vulnerabilities of services within a large system, defining indicators for ensuring security, the architecture of the device capable of repatriating monitoring data in the event of crashes or attacks, and automatic service reconfiguration. Under the frameworks of Bugyo and Deserec, the work is aimed at implementing a system for measuring and maintaining a services safety assurance level (static and dynamic aspects). A tool measuring the department's network safety assurance level was implemented that is capable of estimating not only the safety assurance levels of network components (stations, servers, routers) but also high-level entities like sub-networks and the entire network. Under the framework of Deserec, we designed a robust recovery network (ROSA) dedicated to monitoring and reconfiguring an IS, which measures the robustness of its topology locally and modifies it in order to maximise it. Based on this information, each node selects its neighbours in such a way as to maximise this local robustness. We implemented an application responsible for monitoring and reconfiguring a network. Work was also carried out under the framework of the European CI2RCO and IRRIIS projects on modelling and simulating

the protection of critical infrastructures.

**Trust objects**

Our work [458, 441, 652, 650, 670, 405, 646, 661] is aimed at defining safety points based on chip cards within a complex hardware, software and protocol context involving multiple actors. We proposed the first open application for EAP chip cards, compatible with the Javacard and dotnet market standards, and we integrated these modules into the Windows operating system. We introduced an innovative RADIUS authentication server concept based on EAP cards, and defined new security properties that make use of the benefits provided by dialogue between two high-security elements. In particular, we designed an ID protection mechanism in which critical data are only analysed in an unnumbered form by security modules. We have designed dual SSL batteries (partly onboard) for trust elements, which are compatible with current Web applications, and which effectively combat risks of identity theft and phishing. Recently, we proposed a new concept for RFIDs for the objects Internet; HIP tags. These activities resulted in approximately 30 publications in periodicals and at international conferences, three patents, 2 registered types of software, an industrial prize, a prizewinning project in the OSEO Innovation competitions in 2007 and 2009, and a spin-off.

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