INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team armor

Architectures et Modèles de Réseaux

Rennes

THEME COM

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1. Team

ARMOR is a joint project between the following partners: INRIA, ENST Bretagne, university of Rennes 1, INSA Rennes, CNRS. It has been created in 1999. Since 2002 we have in ARMOR an associate team, PAIR, with the University of the Republic at Montevideo, Uruguay.

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2. Overall Objectives

2.1. Overall Objectives

The main objectives of the project are the identification, the conception and the selection of the most appropriate network architectures of a communication service, as well as the development of computing and mathematical tools for the fulfilment of these tasks. These objectives lead to two types of complementary research fields: the systems' qualitative aspects (e.g. protocols' test and design) and the quantitative aspects which are essential to the correct dimensioning of these architectures and the associated services (performance, dependability, Quality of Service, vulnerability and performability evaluation).
The ARMOR project works on problems related to the design and the analysis of communication services. Such services require functionality specifications, decisions about where and how they must be deployed in a system, and the dimensioning of the different components of the system. The interests of the project concern not only particular classes of systems but also methodological aspects.

Concerning the communication systems themselves, we focus mainly on IP networks and our concerns go from architectural aspects to protocols, studying different aspects of the structure of networks and services: from the topological organization of nodes and links to the software techniques allowing the two current versions of the IP protocol (IPv4 and IPv6) to coexist, from the problems related to the development of architectures allowing to provide specific QoS levels, to security or mobility aspects of the IP protocol.

Interoperability testing is essential to ensure that network components interact correctly before they get deployed in a real environment. As such, it is considered as a part of the standardization process. The Armor project contributes in providing solutions (methods, algorithms and tools) which help in obtaining efficient interoperability test suites for new generation networks, mainly IPv6 related protocols.

From the application point of view, our global field is IP enabled technology in general. We are particularly interested in the "low speed links" world where QoS aspects are very important and lead to many different and exciting problems (on architectural aspects, on routing, on the protocols themselves). We also have activities in pricing methodologies (a critical area for telecommunications providers, with many defying open problems for the near future), in many areas related to the IPv6 technology, in the integration of packet transmission techniques into the next generations of mobile networks, etc.

Related to the previous remarks are the quantitative aspects of most of those problems. In view of this, we develop techniques for the evaluation of different aspects of the considered systems through *models* and through *measurement techniques*. The quantitative aspects we are interested in are performance, dependability, performability, QoS, vulnerability, etc.. The methods we work with go from discrete event simulation and Monte Carlo procedures to analytical techniques, and include numerical algorithms as well. Our main mathematical tools are stochastic processes in general and queuing models and Markov chains in particular, optimization techniques, graph theory, combinatorics, etc. Also in the quantitative evaluation area, we develop

a methodology able to quantify the quality of multimedia flows automatically and in a similar fashion as humans do.

3. Scientific Foundations

3.1. Introduction

Keywords: *IP, Markov chains, Monte Carlo techniques, QoS, Resource allocation, availability, congestion control, dependability, dimensioning, discrete event models, end-to-end protocols, fluid flow models, header compression, high speed networks, interconnection, interoperability, metrology, multicast, multimedia, network reliability, performability, performance, pricing, protocols, queues, reliability, security, service differentiation, simulation, stochastic processes, testing, throughput control, traffic control, traffic engineering.*

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

These foundations are described in the following paragraphs. We begin by a subsection dedicated to Quality of Service, since this concept can be seen as a unifying concept of our activities. Then we briefly describe the specific sub-area of models' evaluation and about the particular multidisciplinary domain of pricing problems.

3.2. Quality of Service

Since it is difficult to develop as many communication solutions as possible applications, the scientific and technological communities aim towards providing general *services* allowing to give to each application or user a set of properties nowadays called "Quality of Service" (QoS), a terminology lacking a precise definition. This QoS concept takes different forms according to the type of communication service and the aspects which matter for a given application: for performance it comes through specific metrics (delays, jitter, throughput, ...), for dependability it also comes through appropriate metrics: reliability, availability; vulnerability for instance in the case of WAN (Wide Area Network) topologies, etc. Moreover, some aspects of QoS have subjective components: the quality of a video stream or an audio signal, *as perceived by the user*, is related to some of the previous mentioned parameters (packet loss, delays, ...) but in an extremely complex way, and with a strong subjective component.

QoS is at the heart of our research activities: we look for methods to obtain specific "levels" of QoS and for techniques to evaluate the associated metrics. Our ultimate goal is to provide tools (mathematical tools and/or algorithms, under appropriate software "containers" or not) allowing users and/or applications to attain some level of QoS, with an optimal use of the resources of the communications system considered. Obtaining a good QoS level is a very general objective. It leads to many different areas, depending on the systems, applications and specific goals being considered. Our team works on several of these areas. We can mention the wide family of routing problems, which in Armor go from graph algorithms to routing techniques specialized to operate in the *last mile* part of the network under extreme performance constraints, our protocol-oriented activities (header compression techniques, interaction between protocols, for instance between IPv4 and IPv6) or the research works around differentiated services. We are also concerned with specific software engineering techniques, namely with middleware technologies in order to hide as much as possible the problems related to resource sharing, scalability and heterogeneity (for instance, such software systems have been successfully used for stationary distributed systems built over fixed networks but they do not suit mobile settings). We also investigate the impact of network QoS on multimedia payloads to reduce the impact of congestion.

3.3. Stochastic modelling

The scientific foundations of our modelling activities are composed of stochastic processes theory and, in particular, Markov processes, queuing theory, graph theory, etc., either for analytical models or for discrete

event simulation or Monte Carlo (and Quasi-Monte Carlo) techniques. We are always interested in models' evaluation techniques for dependability and performability analysis, both in static (network reliability) and dynamic contexts (depending on the fact that time plays an explicit role in the analysis or not). We look at models from the classical so-called *call level*, leading to standard models (for instance, queuing models) and also at the *burst level*, leading to *fluid models*. For this more recent research field, we work both on analytical techniques and on discrete event simulation.

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

3.4. Pricing

Pricing is a good example of a multi-disciplinary research activity half-way between applied mathematics, economy and networking. Indeed, the Internet is facing a tremendous increase of its traffic volume. As a consequence, real users complain that large data transfers take too long, without any possibility to improve this by themselves (by paying more, for instance). A possible solution to cope with congestion is to increase the link capacities; however, many authors consider that this is not a viable solution as the network must respond to increasing demand (and experience has shown that demand of bandwidth has always been ahead of supply), especially now that the Internet has become a commercial network. Furthermore, incentives for a fair utilization between customers are not included in the current Internet.

For these reasons, it has been suggested that the current flat-rate fees, where customers pay a subscription and obtain an unlimited usage, be replaced by usage-based fees. Besides, the future Internet will carry heterogeneous flows such as video, voice, email, web, file transfers and remote login among others. Each of these applications requires a different level of quality of service (QoS): for example, video needs very small delays and packet losses, voice requires small delays but can afford some packet losses, email can afford delay (within a given bound) while file transfer needs a good average throughput and remote login requires small round-trip times. Some pricing incentives should exist so that each user does not always choose the best QoS for her application and so that the final result is a fair utilization of the bandwidth. On the other hand, we need to be aware of the trade-off between engineering efficiency and economic efficiency; for example, traffic measurements help in improving the management of the network but is a costly option.

3.5. Interoperability testing

Interoperability testing is the act of determining if end-to-end functionality between at least two communicating systems is as required by the base standards for those systems. Conformance testing is the act of determining to what extent a single component conforms to the individual requirements of the standard it is based on. We consider that conformance tests are used in order to validate single networks for interoperability purposes. As a consequence, since a couple of years, our research activity focuses on interoperability testing, even though we still have to deal with some issues that apply also for conformance testing. No real formal framework exists in the interoperability testing area, contrary to conformance testing. Our purpose is to provide a formal framework (methods, algorithms and tools) for interoperability testing which helps in obtaining efficient interoperability test suites for new generation networks, mainly IPv6 related protocols.

The interoperability test suites generation is based on specifications (standards and/or RFCs) of network components and protocols to be tested. The model used is an automaton-like structure called IOLTS (Input Output Labelled Transition Systems). It is an LTS which distinguishes inputs, outputs and internal actions.

4. Application Domains

4.1. Application Domains

Keywords: *Extranet, Internet, Intranet, QoS, multimedia, providers, telecommunications, telephony, traffic engineering.*

Our main application domains are those related to network design, at both the transport infrastructure and the service levels. Our expertise currently focuses on IP technology in a variety of contexts (IP QoS, IP security, IP mobility, IP telephony,...), and on analysis and dimensioning tools: telecommunications architecture configuration, bottleneck search, resource allocation policies comparison, etc. Our works on protocols and control mechanisms are also applicable to other technologies besides IP, such as ATM.

Problems arising from the coexistence and interoperability of different technologies are also investigated: between IP and ATM, IP and WDM, IPv4 and IPv6, etc. In the field of traffic engineering and system dimensioning, technological evolution also raises a number of new performance evaluation problems. Besides these main application domains, other important subjects where quantitative analysis plays a central role are, for example, the analysis of control mechanisms, or the problems posed by pricing, which are of evident interest for operators. In the IP world, extensions such as mobile IP, cellular IP, security–related aspects, multicasting, and compression techniques (e.g. header compression) are also important application domains.

The first field in which the team's expertise is requested is the area of IP networks. The usual context is that of an industry member who wishes to develop new techniques, or that of a user who has to set up a new communications system or to upgrade (or more generally, modify) an existing one. This may involve a specific aspect of the system (e.g. the costs model which allows the development of a billing policy), or a particular kind of network (for instance, a home-network), or a family of services (for instance, a security policy).

We can also classify ARMOR's main application domains per type of services involved. Then, the past and current expertise of the team's members mainly involve the transport of multimedia flows over IP, the various network QoS management aspects, the testing techniques (interoperability tests, implementation validation tests – especially for IPv6, and test generation). In this context we find, for instance, problems related to the conception of mechanisms well adapted to specific flow types and QoS goals, both at the network access level, and at the intermediary node level.

With regard to analysis and dimensioning, we contribute to the different related methodologies (measurements, simulation, *analytical* techniques), and also to the development of new mathematical and software tools. We develop models for the collection of specific characteristics of the studied systems (e.g., those related to QoS). We also develop new simulation methodologies, in order to overcome certain limitations of the existing techniques. Finally, it should be noted that networks now offer services with a certain level of redundancy, which leads to problems of reliability. Our team has a long experience in the specific study of this systems' aspect and in related problems such as performability and vulnerability (a notion aiming at quantifying the robustness of a grid without taking into account the reliability of each component).

5. Software

5.1. Experimental platforms

Participant: Laurent Toutain.

We have implemented the Saturne platform, issued for GET funded projects. This platform performs precise one-way delay (OWD) and packet loss rate measurement between two points in IPv4/IPv6 networks. Measurements are performed with a global time reference basis, implemented within GPS synchronization systems installed at each measurement point. The architecture is composed of independent functional modules (Emission, Capture and Data Management) that interact to perform the measurement process. The Saturne architecture has been used in a variety of scenarios including, but not limited to, the evaluation of IP filtering functionalities in a non-specialized router and the validation of diffserv policies in a high-speed network (VTHD Network). In the latter case, it was verified that the results computed by light-weight Saturne are equivalent to those obtained with complex passive tools. We also took advantage of IPv6 capabilities by introducing an extension header for metrology. The proposed method allows to embed metrology information in real IPv6 flow packets.

On VTHD Network we have also deployed the AGAVE platform. We defined a monitor link (extension of OSPF's virtual link) to obtain, in real time VTHD network topology. This topology is used to set up MPLS LSP (label-switched paths).

Saturne and AGAVE are now part of the Network of Excellence EuroNGI (see Section 8.2).

5.2. VISIUM platform

Participants: Laurent Guillo, Cécile Marc, Julio Orozco, Laurent Toutain.

The IETF has standardized the ROHC (RObust Header Compression) protocol. This complex mechanism allows to drastically reduce the header size to increase the performance on slow and noisy links. We have developed a full implementation of this protocol for both the IPv4 and IPv6 protocol stacks. The first testbed used PPP links. This platform will be used with partner in the Cosinus RNRT project.

This protocol has been also deployed in the IRISA VISIUM platform. The TEMICS project-team uses the platform for their work on streaming video and contributes to its development. Their fine grain scalable video coder, WAVIX, can take advantage of its mechanisms allowing to correct bit errors. However, the UDP layer cannot forward data with error bits. Therefore, we are implementing UDP-lite in our platform to allow applications, such as video coders, to receive data even if bit errors still exist. That requires a new ROHC profile dedicated to UDP-lite, which is currently under study. This platform targets also studies on flow control mechanisms for multimedia flow streaming.

5.3. Performance and dependability evaluation

Participants: Gerardo Rubino, Bruno Sericola, Bruno Tuffin.

We develop software tools for the evaluation of two classes of models: Markov models and reliability networks. The main objective is to quantify dependability aspects of the behaviours of the modelled systems, but other aspects of the systems can be handled (performance, performability, vulnerability). The tools are specialized libraries implementing numerical, Monte Carlo and Quasi-Monte Carlo algorithms.

One of these libraries has been developed for the Celar (DGA), and its goal is the evaluation of dependability and vulnerability metrics of wide area communication networks (WANs). The algorithms in this library can also evaluate the sensitivities of the implemented dependability measures with respect to the parameters characterizing the behaviour of the components of the networks (nodes, lines).

We are also developing tools with the objective of building Markovian models and to compute bounds of asymptotic metrics such as the asymptotic availability of standard metrics of models in equilibrium, loss probabilities, blocking probabilities, mean backlogs,...). A set of functions designed for dependability analysis is being built under the name `DependLib`.

5.4. Simulation

Participants: Bernard Cousin, Raymond Marie, Miklós Molnár, Gerardo Rubino, Laurent Toutain, Bruno Tuffin.

We develop different simulation tools, for specific purposes. For instance, we have made contributions to the NIST simulator for ATM networks. We have developed a discrete event simulator called SAMSON, specialized in real time problems (see http://www.rennes.enst-bretagne.fr/~toutain/samson). We have made several contributions to the QNAP language, which is currently a part of the package MODLINE, distributed by SIMULOG.

We currently participate to the design and evolution of the SPNP (*Stochastic Petri Net Package*) tool [128], implemented in more than 200 sites. The main designer is Duke University. Our contributions are on Monte Carlo methods. We plan to increase our participation in the development of this tool.

We are now developing a simulator called `FluidSim`, working in the framework of continuous state models (or fluid models), mainly for performance evaluation of high speed communication networks. `FluidSim` has been already used to analyze ATM networks and the behaviour of TCP. A JAVA graphical interface is being

developed for the modelling and analytical analysis of networks of fluid queues. The tool will be available next year.

In wireless network simulation domain the open source simulator JSIM (cf. http://chief.cs.uga.edu/~jam/jsim) has several extensions to simulate 802.11 based network functionalities. To compare power save mechanisms in wireless networks moduls implementing the Power Save Mode (PSM) of the 802.11 standard have been added to JSIM. The extensions permit to test other power saving mechanisms related to recent works (cf. [70], [71]) .

An OSPF simulator has been developed over `ns2`. This simulator was designed to allow a very fine analysis of OSPF behaviours, convergence time, amount of traffic generated,...It is very important to understand the influence of the Traffic Engineering extension on the OSPF behaviour in large transit networks. Our simulator is used to test and compare different algorithms that build paths using the OSPF database. A pedagogic tool was built over this simulator to explain how OSPF works.

We have enhanced the network simulator NS2 to be able to evaluate the performance of current version of Xcast protocol and to compare it to our proposed extension GXcast. Xxact and GXcsat are explicit routing protocols.

We also propose a new multicast approach, called Simple Explicit Multicast (SEM). This approach uses efficiently branching nodes to build multicast trees and thus deliver multicast packets (see 6.6)

In a similar way, we have enhanced the network simulator NS2 to be able to evaluate the performance of our MMT proposition and to simulate PIM-SM in MPLS networks. MMT promotes multicasting over MPLS.

5.5. IPv6 Integration

Participant: Laurent Toutain.

In collaboration with Jean-Luc Richer (IMAG), we have augmented the functionality of DSTM (Dual Stack Transition Mechanism). This mechanism aims to automatically tunnel IPv4 packets into IPv6 during the transition phase of a given network. The code has been ported to Linux (being originally developed for BSD) and zaurus. We have also been working on securing the address allocation protocol in VPN scenarios. More details are available on http://www.dstm.info web page.

With INRIA/ARES team we have also focused on auto-configuration mechanisms. This allow the automatic deployment of complex topology networks, more precisely on Home Networking Environment. The NAP (No Administration Protocol) has been developed. DHCPv6 Prefix Delegation has also been investigated. NAP tools are available on http://nap.dstm.info.

We have also worked on auto-configuration for the provider point of view. In IPv6 network providers will manage prefixes instead of addresses. We have designed a IPv6 Provider Edge architecture used by the Point6 (http://www.point6.net) to provide IPv6 connectivity across IPv4 network. We have focused our study on interactions betw between PPP configuration, DHCPv6 Dynamic Prefix Delegation and structuration of AAA servers.

5.6. DNSSEC platform

Participants: Bernard Cousin, David Fort, Gilles Guette.

DNSSEC provides security to the DNS infrastructure. We participate to the worldwide deployment of DNSSEC. Our platform is the first French DNSSEC platform, it is interconnected to the international DNSSEC network which is shadowing the usual DNS hierarchy. Our platform offers DNSSEC services provided by primary and secondary servers distributed over 4 locations in France. For more information, see http://www.idsa.prd.fr

We have developed several DNSSEC pieces of software (or patches). All the software of the IDsA project is released under a BSD-like license:

- `verifperl`: a perl “resolver” for DNSSEC. This tool enables to check the chain of trust on which DNSSEC is based.

- `dig-sigchase`: We have patched the well-known administrative tool `dig` to have a "DNSSEC-aware dig".
- `BIND`: A patch to solve a little problem when signing NXT RRs.
- `DNSSECToolKit`: a library which allows to build DNSSEC tools and libraries.
- `Ethereal`: we have done patches for Ethereal to make it more DNSSEC aware (decoding of DS records, computing of key id, etc.). These patches are part of Ethereal since version 10.0a. A second patch, since Ethereal version 0.10.1, has provided the capability to decode RFC2535bis packets (DNSKEY, RRSIG and NSEC), NSD 2.0 and BIND 9.3 exchange such packets.
- `KROd`: a Key Roll-Over daemon tool which enables automatic roll-over of keys for DNSSEC, and automatic conversion from DNS to DNSSEC. This tool uses the DNSSECToolkit to perform all DNSSEC related operations and works with BIND 9.3. It has the following features: it handles ZSK rollover, it handles KSK rollover and it communicates securely with the parent server to ask for the keyset update, most key/signing parameters can be specified to KROd, a control channel ala zebra, and it can be used to migrate a normal DNS zone to a DNSSEC zone quite easily (KROd does nearly all the key/signing jobs for you), it can save and reload its configuration, this is useful when a crash occurs (note: at the moment KROd is not completely stateful).
- `GDS`: the BIND patch that changes the behaviour of BIND when processing DS records. This includes a modification of the BIND server and a modification of the dnssec-signzone tool. Generalized DS allows to have build a DNSSEC chain of trust over a succession of secure and unsecure domains (a domain that has unsecure parents).
- `libsresolv`: it is a library built within the BIND toolkit. It comes as a patch over the BIND 9.3 sources. It contains a DNSSEC resolver and validator. The goal is to show everything that can be proved from a DNSSEC answer. The validator provides positive or negative answers (it can prove that a domain doesn't exist), it can also prove that some domains are empty non-terminal ones. `libsresolv` performs bottom-up validation, it is signature oriented.

All this software is available at http://www.idsa.prd.fr.

5.7. Network Graph and Path Computation experimental prototype

Participants: Bernard Cousin, Thierry Feuzeu, Alexandre Guitton, Miklós Molnár.

We are implementing a functional demonstrator of a novel architecture for distribution area networks. The provided flexible broadband serving network adapts to the operators' topology and enables an enhanced services portfolio. The architecture is based on a non-regular mesh networks of switching nodes. A Serving Network Controller provides self-configuration and intelligent management of the switching nodes. Our demonstrator provides algorithms for the auto-configuration, data path routing and fast rerouting in case of link or node failure.

5.8. Internet Protocols Interoperability Testing Platform

Participants: César Viho, Annie Floch, Anthony Baire, Frédéric Roudaut, Bruno Deniaud, Ariel Sabiguero.

We have built a platform with almost all existing IPv6 existing free stacks. We have developed a set of conformance executable test suites for IPv6 related protocols (MIPv6, 6to4, NAT-PT, RIPng, etc.) using the v6eval tool of the Japanese TAHI project. All these test suites are freely available at http://www.irisa.fr/tipi. This platform allows both conformance and interoperability testing. The test can be done remotely.

We have started also to develop conformance test suites using the DANET TTCN3 based test development toolkit. This work is done in tight cooperation with the DANET company in Germany. Templates for IPv6 packets have been defined. An extended version of Ethereal has been developed allowing IPv6 stacks testing

using an Ethernet layer service. We have already some TTCN3 based executable test suites for the RIPng and the OSPFv3 protocols. This test suites are also available at http://www.point6.net.

6. New Results

6.1. Pricing

Participants: Yezekael Hayel, Patrick Maillé, Ricardo Orozco, David Ros, Bruno Tuffin.

Pricing is probably one of the most efficient means to control congestion in a communication network. It is furthermore mandatory for service differentiation.

Our work this year has focused on pricing schemes without bandwidth reservation [68]. It can be decomposed into two main categories: auctioning for bandwidth, and, in a general way, pricing and scheduling.

The first main category is thus auctioning for bandwidth. Our work in this field has been inspired by the progressive second price (PSP) auctions developed at Columbia University [137]. Nevertheless, this pricing scheme presents some drawbacks, such as a time and efficiency-consuming convergence phase and a signalling overhead due to broadcasting the bid profile after each change of bid. These drawbacks have been tackled in [13], the costly iterative scheme has been replaced by a one-shot multiple-bid scheme keeping the optimality and incentive compatibility properties. This scheme has been adapted in [81] to multicast flows competing with private flows and to the case of an access network through a tree topology [32]. Another adaptation to the case where the utility of getting a given bandwidth depends on the history of allocations (fitting the framework of multimedia for instance) has also been obtained in [80].

Multi-class pricing is also an important research topic of our group [11]. Following a previous work establishing that, in order to increase its revenue, an ISP should use at its routers a priority scheduling mechanism rather than generalized processor sharing [127] in the case of a simple queuing system, we have extended the result to the case of TCP traffic in competition, since it can modeled at the flow level by a discriminatory processor sharing queue [69]. We have thus focused on priority pricing in [28], where Aumann-Shaphey prices (that fairly share the total perceived cost) optimizing the social welfare are determined. Similarly, we have studied the pricing of CDMA (wireless) networks using multiple classes [102]; optimal (in terms of ISP revenue) static prices are determined. In [18], we have designed a pricing scheme for a RED buffer such that the drop probability (or more exactly the slope of the drop curve of RED) depends on the willingness to pay of the users: the more you pay, the less one of your packets is likely to be dropped. The problem is modelled as a non-cooperative game and conditions for an equilibrium to exist and to be uniquely defined are established.

As other works on pricing, in [27], we have studied a simple and promising pricing method called the "Cumulus Pricing Scheme", dealing with service differentiation and scalability issues. We have mathematically determined parameters optimizing the provider's revenue under the constraint that each user has an incentive to reveal his anticipated bandwidth consumption. In [110], we have developed in reliability-dependent pricing scheme assuming that the network is uncongested thanks to optic fiber; end-to-end reliability is then the property of interest. In [60], [29], a related problem, yield management for computing infrastructures, has been studied in collaboration with IBM, Yorktown Heights. A framework for modelling and analysing the benefits in a scenario of complex dependence of sojourn times of jobs on factors like customers' choice has been considered.

6.2. Dependability and extensions

Participants: Raymond Marie, Gerardo Rubino, Bruno Sericola, Bruno Tuffin.

We maintain a research activity in different areas related to dependability, performability, vulnerability analysis of communication systems. In 2005 our effort has been on evaluation techniques using both the Monte Carlo and the Quasi-Monte Carlo approaches. For what concerns the analytical evaluation of dependability measures, we obtained new results on the computation of the moments of such measures by using the

stationarity detection. In [33], we study a passive r/n redundancy including failures at activation instants ($i.e.$, redundant elements only operate in case of failure of working elements and have a non negligible probability of failing at the instant of activations). Under Markovian assumptions, we obtain recurrent and numerically stable expressions of the steady state unavailability, of the MTBF and of the expectation of the first up-time.

Monte Carlo methods represent the single tool to solve very large Markov chains. When dealing with rare events, as in the case of dependability evaluation, acceleration techniques, such as importance sampling, have to be used. In a previous work [140], we have defined the so-called Bounded Normal Approximation (BNA) property, stating that the normal approximation, and thus the confidence interval coverage is kept bounded as rarity increases. In [52], [53], we discuss and relate all robustness measures of rare event estimators: Bounded Relative Error (BRE), BNA and Asymptotic Optimality (AO). We also illustrate on a static reliability estimation problem that they might of the two important components of efficiency: the computational time. We thus define the so-called Bounded Relative Efficiency and Generalized BNA properties which encompass this component. A practical analysis of the coverage is also provided. In [91] we describe how to efficiently compute the sensitivities of the basic network reliability metric in a static context using Monte Carlo, when the failure of the system is a rare event.

In Quasi-Monte Carlo (QMC), the error when estimating an integral uses a deterministic sequence (instead of a random one) called a low discrepancy sequence and having the property to spread quickly over the integration domain. The estimation error is bounded by the product of a quantity depending on the discrepancy of the sequence and the variation of the integrand. But this bound is proved to be useless in practice.

By combining MC and QMC methods, we can benefit from the advantages of both methods: error estimation from MC and convergence speed from QMC. In [96], we have continued this work. We have especially the validity of the coverage of the resulting confidence intervals. In [105], it is also shown how, by using QMC (or its randomized version) for a small amount of coordinates, and MC for the remaining ones, the accuracy of the simulation can be improved. The gain is theoretically proved, as well as illustrated on finance problems.

As another remark, due to the correlation structure of the sequence, necessary to “minimize” the error, the direct application of QMC methods to the analysis of Markov chains was inefficient. In [130], we had developed a QMC method analyzing the transient behaviour of discrete time Markov chains using only a two-dimensional low discrepancy sequence. The main characteristic of this method is a relabelling of the chains at each time step of the simulation. In [103], [75], the method is adapted to randomized QMC methods and to the case of Markov chains with random horizon (so that regenerative can also be considered). The superiority of the method with respect to those in the literature is again illustrated, as well as proved in some situations. The method is also shown in [56] to improve the simulation of rare events, when combined with importance splitting techniques.

6.3. TCP

Participants: David Ros, Bruno Tuffin.

As a consequence of last year’s collaboration with Maestro project-team through the TCP and PRIXNET ARCs, we have analyzed the behaviour of two competing TCP connections sharing a common bottleneck link. We have analyzed several loss strategies: fixed loss probability, largest throughput loss or proportional loss. After some derivations in the general asymmetric case, we especially show that in the symmetric, surprisingly, the loss strategy has no consequence on the average throughput. We show, in contrast, that the second moment of the throughput does depend on the strategy [19]. This invariance result has been extended in [97] to more than two connections in competition. This is shown to be of practical importance as it elucidates the throughput of parallel TCP sockets, an approach used widely to improve throughput performance of bulk data transfers (e.g. gridFTP). The validity of the result has also been illustrated through ns simulations.

6.4. PSQA: Pseudo-Subjective Quality Assessment

Participants: Gerardo Rubino, Martín Varela.

This research work is part of the activities of the associated team PAIR (see 8.4).

PSQA is a methodology which allows to quantify the quality of a video or audio (or multimedia) stream at the receiving end, after said stream has passed through a packet network such as the Internet. This quantification is done automatically, and in real time if necessary. The specificity of the approach is that the evaluation obtained is very close to the evaluation that could be done by human observers. The reason is that we use a specific statistical learning tool to capture how humans react (from the perceived quality point of view) when receiving these flows. The tool learns and then behaves similarly to real observers. The statistical tool used to this end is the Random Neural Network model, which is an open queuing network with positive and negative customers. The basic initial papers are [133] for video flows and [134] for audio communications.

To the best of our knowledge, PSQA is the only solution to the problem of assessing the quality of a multimedia stream after travelling through a packet network with the given properties: automatic, real-time if necessary or useful, and accurate (close to the evaluation performed by real human observers). In addition to being able to provide real–time assessments, this approach does very well compared to other metrics proposed in the literature [17] providing better correlation with subjective assessments. This year, we explored its application in a wireless context in two papers: [48] and [22]. The former discusses general issues related to the perceived quality in such an environment. The latter presents material associated with control issues. In [38], a general presentation of PSQA is provided, with new elements concerning sensitivity computations. This is a consequence of the nice mathematical properties of the RNN tool. See also [17] for a global presentation of PSQA in the case of audio signals.

6.5. Network Design

Participants: Franco Robledo, Gerardo Rubino.

This research work is part of the activities of the associated team PAIR, and is being jointly done with M. Héctor Cancela (PAIR Uruguayan project leader), from the University of the Republic of Uruguay, in Montevideo.

This team has been put in place in 2000, and its main objectives were the development of techniques and tools for Wide Area Network (WAN) topology design and the development of a way of quantifying perceived quality. For the latter topic, see 6.4.

The problem of WAN topology design is usually decomposed into two main parts, the design of the backbone network (usually with a meshed topology) and the design of the access network (usually with a tree-like or forest-like topology); the objectives usually taken into account is the minimization of the cost of the network topology, but we also consider other performance, dependability, or more in general user perceived quality metrics in this design process. This year we finished a doctoral work on the topic [15], and the balance of the work is as follows.

In the first two years, there was an important effort in the direction of studying and developing effective metaheuristics for this kind of network design problems. In particular, after exploring other alternatives (see [123], [124], [117] for example), we selected GRASP, the Greedy Randomized Adaptive Search Procedure heuristic, as our main optimization technique. This method gives very good results (although it does not guarantee optimality), and works as a template, within which other heuristic ideas can be incorporated. During 2003 we employed this method for the design of a backbone with reliability (connectivity) restrictions, our first results in this area were published in [118], [119]. In 2004 we continued exploring the potential of the GRASP technique, obtaining results on a more complete test suite for the backbone problem [120], and tackling the access network design problem. For this last problem we used different heuristics as building blocks for the GRASP method, among them the Random Neural Networks that are also being employed with good success in our technology PSQA (see paragraph 6.4). The method was tested on a large test suite with very good results, which were the object of two publications [122], [121].

This year we published in [51] a technique allowing the design of a pseudo-optimal topology for the access network. We used GRASP as the general approach and different local improvement techniques such as RNN. See also [15] for a global view of the work developed in the area during the last 3 years.

6.6. Low speed links

Participants: Laurent Guillo, Louis-Marie Le Ny, Cécile Marc, Elizabeth Martinez, Julio Orozco, David Ros, Gerardo Rubino, Bruno Sericola, Laurent Toutain.

If most of the QoS-related problems in the core network can be solved by overprovisioning, congestion may continue to arise in some specific cases: when the bandwidth is either physically limited, like in UMTS networks, or if traffic rerouting due to link failure may lead to an overload. Specific research themes and contributions of ARMOR in this context are the following:

- **Header compression techniques (ROHC protocol) in IPv6**. The performance of IPv6 in the radio link can be improved using header compression algorithms. The 3GPP (3rd Generation Partnership Project) consortium has adopted the ROHC (Robust Header Compression) algorithm of the IETF (Internet Engineering Task Force) [113] standard track for the real-time applications using RTP/UDP/IPv6 and UDP/IPv6. We have developed one of the first IPv6 implementations of this protocol. This allowed us to propose several enhancements in order to support more efficiently IPv6 [132] or to study parameters impact on performances. Collaborative works with the TEMICS project-team lead us to study a new ROHC profile dedicated to UDP-lite. Always in collaboration with the INRIA project TEMICS, we will study the impact of the residual transmission error on multimedia flows, in order to evaluate the QoS perceived by the user.
  As a first result of these efforts, we present in [25] the analysis of the proposed standard ROHC deployed in an UMTS radio link and discuss different schemes to increase compression performance. The results are based on our IPv6 implementation of the ROHC header compression algorithm and on a simple and accurate analytical model used to evaluate the packet loss probability.
  We have worked on interaction between ROHC Unidirectional flows and multicast. We have studied the behaviour between these two layers and propose a solution to reduce delays when a receiver subscribes to a multicast flow [82]. We are also studying the behavior of ROHC on IEEE 802.x network to also services such as Voice over Wi-Fi. We have studied the behaviour of tunnelled flows [108], especially in NEMO context. Finally, with the INRIA ARES team we are using this proposal to work on ad-hoc architectures.
- **Active queue management for diffserv**. In the context of the diffserv architecture, active queue management (AQM) algorithms are used for the differentiated forwarding of packets. We have proposed a new active queue management algorithm, which we call Adaptive RIO (A-RIO), aimed at both easing the configuration of diffserv routers and building services with loose delay guarantees (thesis of Julio Orozco [14]). Some issues regarding the performance of A-RIO (like fairness among flows) have been explored in [35].
- **Multimedia tagging for diffserv** When multimedia flows are transported on an IP network, congestion may lead to a severe degradation of the perceived quality if important information of the multimedia stream is lost. We have worked on the sequel of Octavio Medinas PhD thesis [131], focusing in new video coding schemes like H.264, which are designed with network error resilience in mind and allow for more flexible tagging strategies [135]. We have also explored how to quantify the relative merits of different tagging strategies, in terms of the resulting subjective quality, by means of neural networks and the PSQA approach [14].

6.7. Autoconfiguration

Participants: Bruno Sericola, Laurent Toutain.

We studied in [100] a model for the NAP protocol, dedicated to the auto-configuration of IPv6 routers. If the auto-configuration of hosts is defined by IPv6 and mandatory, IPv6 routers still have to be manually configured. In order to succeed in new networking domains, a full auto-configuration feature must be offered. NAP offers a fully distributed solution that uses a link state OSPFv3-like approach to perform prefix collision

detection and avoidance. In this report, we present a model for NAP and analyze the average and maximum autoconfiguration delay as a function of the network size and the prefix space size.

6.8. Wireless networking

Participants: Jean-Marie Bonnin, Bernard Cousin, Hanen Idoudi, Miklós Molnár.

We study communication problems, QoS management, adaptation of flows and energy used in wireless (mainly ad hoc) networks in cooperation with the laboratory CRISTAL of ENSI, Tunisia. The IEEE 802.11 standard proposes an efficient Power Save Mode (PSM) to spare battery energy in wireless network component. One of the drawbacks of the PSM manifests in the latency implicated by missing nodes in the case of routing. In order to decrease the latency, we proposed a model for the energy conservation, based on synchronized alternations of “on” and “off” states of network activities of the ad hoc network components [70] [71].

Despite IEEE 802.11 is now widely deployed over the world, this wireless LAN technology has drawbacks that prevent multimedia applications to work properly. Using simulation study we shown (in collaboration with Thomson) in the 2006-paper [139] that IEEE 802.11 networks have strong QoS issues in triple play home networks even using IEEE 802.11e (WMM), which is the standardisation of a QoS differentiation mechanism for WiFi networks.

Multimedia services are a major application for IEEE 802.11 WLANs and they often use multicast to reach several users on the same WLAN without consuming to much resources. The current standard does not utilize rate adaptation technique for multicasting and this prevent applications using multicast to take advantage of the broadband (up to 54 Mb) capacity of the current WLAN technologies since they have to fall back on a lower rate (often 1 or 2 Mb). We propose a new rate adaptation mechanism (SARM: SNR-based auto rate for multicast) for multicasting multimedia content in IEEE 802.11 WLAN environments. It will appear in [136].

In order to propose improvement for the next generation wireless LAN, we worked in collaboration with Seoul National University on a wireless packet scheduling algorithm [39] that uses the multi-state (multi-rate) wireless channel model and performs the packet scheduling by taking into account the channel usage time of each flow. We also studied a new contention avoidance mechanism using “superslot” and “pseudo-collision” concepts [92].

The norm IEEE 802.11i aims the authentication and the key distribution in wireless networks. We proposed two new secure mechanisms for fast re-authentication in handover operations [74], [73]. This work will be extended to propose a new solution for inter-technologies (WiFi-WiMAX) handover management in an operated mobile infrastructure.

6.9. Security

Participants: Bernard Cousin, Gilles Guette.

Nowadays, reaching services on the Internet highly depends on the use of the DNS (Domain Name System) infrastructure, and DNS security has become strictly necessary. Moreover, such a secure infrastructure (DNSSEC) could be used to secure other applications. The goals of our project are the study and deployment of secure DNS transactions, the development of mechanisms allowing the use of the DNSSEC infrastructure to distribute keys and certificates for secure signalization of Mobile IPv6 and use of IPsec (HIP and/or opportunistic IPsec).

Last year we have analyzed the DNS threats, studied the completeness of DNSSEC and IPsec and specified the requirements for key rollover for DNSSEC [126]. A France-wide DNSSEC platform has been deployed, it is connected to the international DNSSEC, which shadows the standard DNS. We are particularly interested by the automation of key rollover process and the key management process. The DNSSEC validation process is based on the establishment of a chain of trust between zones. This chain needs a starting point called a trusted key. During the deployment phase, secure zones and unsecure zones could coexist simultaneously. Every resolver has to get a copy of the trusted key for every island of security. Currently we study the trusted

keys' rollover problem and two algorithms to solve it. The first one is resistant to key-compromise and places the choice of security level in the resolver's administrator side, which is a natural way to protect a resolver [62]. The second one enables an automatic and smooth exchange of secure keys when an unsecure zone becomes secure and reduces considerably the number of trusted keys needed in a resolver [63], [64].

The illustration and validation of our concepts, with DNSSEC patches and tools, can be found at http://www.idsa.prd.fr. A global view of the results in this area, over the last 3 years, can be read in [9].

6.10. Queuing analysis

Participants: Louis-Marie Le Ny, Gerardo Rubino, Bruno Sericola.

We have developed an algorithm to compute the sojourn time distribution in the processor sharing, single server queue with Poisson arrivals and phase type distributed service times. In a first step, we established the differential system governing the conditional sojourn times probability distributions in this queue, given the number of customers in the different phases of the PH distribution at the arrival instant of a customer. This differential system is then solved by using a uniformization procedure and an exponential of a matrix. The proposed algorithm precisely consists of computing this exponential with a controlled accuracy. This algorithm is then used in practical cases to investigate the impact of the variability of service times on sojourn times and the validity of the so-called reduced service rate (RSR) approximation, when service times in the different phases are highly dissymmetrical. For two-stage PH distributions, we give conjectures on the limiting behaviour in terms of an $M/M/1$ PS queue and provide numerical examples to illustrate the different approximations. These results have been published in [40].

We also obtained new results on the transient analysis of averaged queue length in [37]. This work consists in the analysis of an exponentially averaged queue length over a finite interval of time. Such studies are useful in the context of active queue management where packets are dropped according not only to the current state of the queue but also by considered its past states.

In [77] we have studied a queue with two classes of customers, a single server and FIFO discipline. Class-i ($i = 1, 2$) customers arrive according to Poisson processes; there is no priority between the two classes. The service of class-1 customers is exponential whereas class-2 customers are served instantaneously. We have obtained exact formulas of geometric form for the stationary probability of each ordered state and for the steady-state distributions of customer numbers in the system.

Using the concept of duality between stochastic processes as defined in "Continuous-Time Markov Chains" (W.J. Anderson, 1991, Springer-Verlag), we developed a new approach to obtain closed-form expressions of transient distribution for basic Markovian queues. The idea is to go to discrete time through uniformization, then to use duality to map the problem into transient analysis of absorbing models and then, to use combinatorial techniques to analyze these absorbing chains. See [31] for recent results on this approach.

6.11. Analytical fluid models

Participants: Raymond Marie, Bruno Sericola.

In [34] we published a chapter introducing fluid models, devoted to the practitioners in the field of telecommunications.

On the basis of the simple formulae and precise algorithms that we had obtained for the distribution of the buffer content of a finite or infinite capacity fluid queue [138] fed by a Markovian queue or by an M/M/1 queue [112], we have obtained in [36] an algorithm to compute the transient distribution of a fluid queue driven by a birth and death process whose birth and death rates are suggested by a chain sequence, for which the stationary probabilities do not exist.

The transient analysis of a fluid queue driven by an M/M/1 queue has been considered in [41] and the general case of the birth and death process has been studied in [65] by means of results from spectral theory.

6.12. Interoperability Testing

Participants: Alexandra Desmoulin, Francine Ngani, Ariel Sabiguero, César Viho.

Any real formal framework does not exist for interoperability testing area, contrary to conformance testing. Our purpose is to provide a formal framework (methods, algorithms and tools) that helps in generating efficient interoperability test suites. The model used here is an automata-like structure called IOLTS (Input Output Labelled Transition Systems). It is an LTS which distinguishes inputs, outputs and internal actions.

We have proposed a formal definition of the notion of interoperability, which has been considered by the testing community as one of the first real contributions in this area [111]. This year we have studied the problem of quiescence management in interoperability testing. We prove that by taking into account potential quiescence of implementations, we can improve interoperability testing [59], [101]. Based on this results we developed algorithms that generate more accurate interoperability tests [57], [58].We also study how a distributed approach (including remote approach) can help in efficiently testing components [42].

We have also developed methods and algorithms using formal methods for automatic conformance and interoperability tests generation for mobility protocols. The Mobile IPv6 (MIPv6) have been used to validate these algorithms [88], [87].

We have proposed some solutions for some issues regarding the last step of testing activity, where abstract test suites are translated to obtain executable test suites that are executed against real implementations. The new standardised TTCN3 language and the RIPng protocol have been used for this purpose [94], [93].

On a pragmatic side, we try to validate our solutions for new generation network, mainly IPv6 related protocols. We have generated conformance and interoperability tests for significant IPv6 and 3GPP related protocols, like MIPv6 (Mobile IPv6), IPv4-IPv6 transition mechanisms (NAT-PT, 6to4), RIPng (Routing Internet Protocol for IPv6), etc. These tests have been used for many interoperability events such as the ETSI/Plugtest events (since 2000), and the Japanese TAHI events (since 2001).

We are also involved in the “IPv6 Ready Logo Programme” (see http://www.ipv6ready.org) which is a world wide certification programme launched by the IPv6 Forum. We are responsible of the definition of technical requirements for the two phases of this programme. The Phase I started two years ago with real success. The second phase started this year, with stronger requirements.

6.13. Mobile networks

Participants: Jean-Marie Bonnin, Lucian Suciu.

For three years now, the ARMOR team has launched several activities having the common key work: mobility. Some of these activities belong to other subgroups such as the TEST subgroup. Two mains theme set up the core of this new subgroup: Mobile Access Networks, Ubiquitous Terminals and Networks in Motion.

Operators are interested in the adaptation of existing micro mobility solutions to their operational constraints. Hence, we have participated, in collaboration with France Telecom R&D, to the development of a new micro mobility protocol derived from HMIPv6. This protocol allows the network to take in charge the handover decision. Then the network can prepare the handover to reduce the latency time and perform load-sharing taking into account the overall situation of the network. The new protocol (NCHMIPv6: Network Controlled HMIPv6) is being improved to provide quality of service management in access network.

We are also involved in the definition of a new architecture that allows the applications to be able to adapt efficiently and timely their behaviours to network condition changes. This leads us to deal with automatic interface choice and automatic configuration, as well as with the relation between the network and terminals in term of security and quality of service (on-going work). We have also defined a framework to build adaptive application and to manage network resources description thru a profile mechanism. This work has been recently extended to address the multi-interfaces management in the case of a mobile router [95]. Note that, NEMO (Network in Motion) and its application to Intelligent Transportation System is becoming one of our important topics.

6.14. Optical networks

Participant: Nizar Bouabdallah.

Our work focuses on two main technologies that seem to be contradictory: optical and wireless networks. However, to paraphrase from [125], we can think of optical fiber and wireless communications as quite complementary. Optical fiber doent go everywhere, but where it doe go, it provides a huge amount of available bandwidth (well over tens of terabits per second over a single fiber). Wireless, on the other hand, does go almost everywhere, but provides a highly bandwidth-constrained transmission channel, susceptible to a variety of impairments.

Optical fiber communication is now ubiquitous in the telecommunications infrastructure. Fiber optics and wavelength-division multiplexing (WDM) technology have increased significantly the transmission capacity of today's transport networks, and they are playing important roles in supporting the rapidly increasing data traffic. Nonetheless, the rigid and large routing granularity (i.e. wavelength) entailed by such an approach could lead to bandwidth waste. In our work, we propose and evaluate a new concept of traffic aggregation in WDM optical networks that aims at eliminating both the bandwidth underutilization and the scalability concerns that are typical of all-optical wavelength-routed networks [114]. Our objective is to reduce the network cost while preserving the benefits of all-optical wavelength-routed networks. In order to assess the efficiency of our proposal, all underlying network costs are compared. Our results show that the proposed aggregation technique can significantly improve the network throughput while reducing its cost [49].

On the other side, wireless communication is now firmly established as the preferred means of communication for signals over a few megabits per second over distances more than a few hundred meters. Future wireless networks are expected to provide IP-based coverage and efficient mobility support with end-to-end Quality of Service (QoS) requirements. In this work, we propose a new architecture that supports both mobility and QoS management in wireless MPLS networks [129]. To achieve this, we propose a new micro-mobility management scheme called Micro Mobile MPLS [76]. Our proposal includes two protocol variants. In the first variant called FH-Micro Mobile MPLS, we consider the fast handoff mechanism, which anticipates the LSP procedure setup with an adjacent neighbour subnet that an mobile node (MN) is likely to visit. This mechanism is proposed to reduce service disruption by using the link-layer (L2) functionalities. In the second variant called FC-Micro Mobile MPLS, the forwarding chain concept, which is a set of forwarding path, is provided to track efficiently the host mobility within a domain. This concept can significantly reduce the registration updates cost and provide low handoff latency.

6.15. Trafic Enginneering

Participants: Bernard Cousin, Alexandre Guitton, Raymond Marie, Miklos Molnar, Joanna Moulierac, Iméne Chaieb, Wojtek Bigos, Shadi Jawhar, Thomas Legrand.

Dependability and efficiency in routing and QoS management have to be improved for high speed networks. Our research on this domain is focused on the management of Optical Networks. Some of these works are connected to other works described in the multicast chapter.

Backbone data networks evolve towards all-Optical Networks. In such networks IP routers are interconnected by re-configurable optical cross-connects (OXC) managed by an automatic control plane. This architecture, on the one hand, improves the overall network performances by providing advanced functionalities such as optical by-pass, traffic engineering and fault protection mechanisms but, on the other hand, introduces an additional switching layer which increases the overall network cost. A general presentation of some of the main problems can be found in [72].

In previous works, we have proposed several heuristic for multicast tree construction. These polynomial time approximations take into account some specific constraints of optical networks: QoS constraint, lightwave constraint and/or constraints on specific resources from optical switches (I.e. limited availability of light splitters, light amplifiers, light swappers, etc.). Some of these works are described in [10].

Moreover, we have previously proposed to use an enhanced architecture which introduces an intermediate layer based on MPLS [23]. This architecture introduces some independance and flexibility in the network management. This multi-layer architecture have lead us to consider modelling techniques which enable us

formulate and to solve various design problems, including multi-layer modelling of networks comprising different technologies [46] and incorporating network recovery mechanisms [45], [47].

Dependability is the ability of a network to cope with failures, *i.e.*, to maintain connections established even in case of failures. IP routing protocols (such as OSPF and RIP for instance) do not fit dependability objectives of today applications. Moreover, forwarding technique based on destinatination address (like IP) produce a many to one routing scheme where all paths sharing the same destination must share their protection scheme: protection scheme of paths having the same destination must be established in a coordinated way. In this work [85], we propose fault recovery for many-to-one routing scheme based on preplanned protection. The main advantage of our approach is that recovery in case of failures is achieved within a short delay. Additionnaly, with respects to other approach, the dependability of the routing scheme is increased because we prove that it statistically withstans more failure types and locations. For each routing scheme our algorithm computes a multi tree where the primary tree could be choosen arbitrarily (for instance the shortest path tree) and the backup tree could be obtain efficiently.

6.16. Multicast Routing

Participants: Ali Boudani, Bernard Cousin, Thierry Feuzeu, Alexandre Guitton, Raymond Marie, Miklós Molnár, Joanna Moulierac.

Scalability and efficiency of routing, QoS management and tree construction have to be improved for multicast traffic. For a global description of our contributions, see [26] and [23]. Our research on multicasting can be organized in several thematic axis:

6.16.1. Tree Construction

In optical networks the constraints for routing algorithms follow from the physical constraints of optical links and switches. One of the fact which restricts well known multicast routing algorithms in WDM networks is that the splitting capability of messages is missing. In order to adapt multicast routing algorithms to WDM networks and improve their efficiency, a new way of doing multicast on wavelength-routed optical networks was proposed. A summary can be found in [10].

6.16.2. Digital TV, IP and MPLS Multicasting

Our research has been deployed in the domain of digital TV broadcasting. More specifically we have proposed an effective way to transfer TV media in a unified framework. This framework enables the easy integration and management of distributed broadcasting systems which are built with heterogeneous equipment [54]. The goal of this work is to specify an optimised transfer mechanism, this mechanism is integrated in a unified framework managing digital TV content. Our transfer mechanism provides an abstraction level for different network infrastructures and protocols in a seamless way, taking advantage of each of these technologies. For example, multicast and QoS features are supported and managed, as far as they are provided by the underlying network interfaces. Moreover, striped and partial Media Asset transfers are handled independently of the network infrastructures, at the Application layer.

We have proposed several enhancements for efficient management of multicast tree either for plain Internet data network [99], [24] or for internetworking over MPLS infrastructure [99], [50]. Using Internet over MPLS provide the efficiency and traffic engineering capability given by label switching and the flexibility given by Internet. In this context we have proposed to detect branching nodes and to use LSP to minimize the working load induced by multicast routing. A simulation platform has been extended to analyze the multicast traffic over MPLS.

6.16.3. Explicit Group Multicast

We have enhanced Explicit Routing Technique, which enables routing of small groups on Internet. Our proposals decrease packet overhead, enable management of larger groups, and segment efficiently the packet. We have proposed an extension to the Xcast protocol [116]. Our proposition is an adaptive protocol which generalizes the Xcast forwarding method and may be parameterized to fit the size of the group. Our protocol is

as efficient with small groups as the original Xcast family protocols and it can manage more efficiently larger groups [115]. This solution has been proposed in an IETF draft .

Xcast like explicit multicast routing procedures implicate the overload in the concerned routers. Tree based explicit routing solutions can appease the overload with explicit coding of the diffusion tree. The actually known tree based explicit multicast routing protocols do not handle the fragmentation of forwarded packets. We proposed a new tree based explicit multicast routing protocol which can handle the packet fragmentation and which permits the use of the tree based routing even if the multicast group is large. A first description of the routing problem and the proposed solutions is presented in [10].

6.16.4. Label Switching

We propose a bridging method based on label switching. This method produces no overhead: labels are located into the Destination Address header field, but gives high flexibility. This flexibility can be used to efficiency manage QoS or multicast traffic. A prototype is developed to measure the performance of our proposition [61].

6.16.5. Multicast Tree Aggregation

Multicast is not scalable in IP due to the number of forwarding states needed in routers. The aggregation of the used multicast trees is a recent proposition to decrease the number of used trees and so the number of forwarding states in the routers. The previously proposed algorithms for tree aggregation need important computation capacities and time. To simplify the tree aggregation a fast algorithm was proposed in [67]. Generally, the aggregation algorithms do not handle the QoS needs of multicast communication requests. A solution to handle the bandwidth environment of multicast communications was elaborated in [86].

7. Contracts and Grants with Industry

7.1. Cyberté: Multiple Network Interfaces Optimized Support for an IPv6 Mobile Terminal

Participants: Jean-Marie Bonnin, Lucian Suciu.

Cyberté is a RNRT project, starting in January 2002, and ending in December 2005. The project leader is France Télécom R&D. ARMOR's budget is 174 Keuro. The other partners are Cisco France and the LSIIT.

This project belongs in the field of Mobile Networking, and its main goal is the improvement of QoS in heterogeneous mobile network environments. This improvement is done by a better management of inter– and intra–technology handovers in wireless networks (such as Bluetooth, WiFi, or HiperLAN), both in home and enterprise environments. Our main contributions to this project are: the design of a new architecture able to provide information to adaptive applications and to automatically select the best suited interface according to application needs, and development of adaptive applications, capable of adjusting their needs according to the available resources.

7.2. Ubique: QoS Profile Management and Interface Selection

Participants: Jean-Marie Bonnin, Lucian Suciu.

Ubique is a CRE project (France Telecom funding and partnership) and ARMOR's budget is 166 Keuro. The project ended in February 2005.

The domain of the Ubique project is that of IP mobility, and its main goal is the design of a QoS profile management and interface selection algorithm. The growing popularity of wireless interfaces will make that mobile computers have several network (wired and wireless) interfaces. It is then likely that the system will be frequently forced to change the active interface(s), which currently implies the closing of running applications, or even a reboot. The user will then need mechanisms that allow for the selection of the most appropriate

interface, following the available network access points, applications' needs, and the cost of the different connections. Several patents based on this work have been issued by France Telecom.

7.3. Probabilistic test generation

Participants: Hélène Le Guen, Raymond Marie.

This was a CIFRE contract (2002–2005), in which ARMOR's budget was of 90 Keuro. The goal was to develop software for testing new communication protocols. The associated PhD thesis with this collaboration has been presented in [12]. The subject of this PhD concerns the use of Markovian models to assign a coverage measure to the tests done during a test campaign. It also aims to find techniques to improve the effectiveness of these tests. Let us note that the Award for innovation at this year's RTS (Real Time System) Trade Fair went to the company All4Tec for its Matelo (Markow test logic) software, which was developed in part thanks to the work of Hélène le Guen.

7.4. Fast reroute

Participants: Bernard Cousin, Miklós Molnár, Yazid Saidi.

Fast reroute is a CRE project (France Telecom funding and partnership). The project spans 24 months.

MPLS-TE technology enables the establishment of efficient point to point or multipoint connections which should offer strict QoS guarantee. MPLS Fast Reroute proposes pro-active protection of the network connections based on pre-established backup paths. The main goal of our project is, first, to select the best paths for the backups (each backup could be shared between several connections), second to evaluate the bandwidth which should be allocated to each backup.

7.5. IPv6 Interoperability Methodology

Participants: César Viho, Bruno Deniaud, Frédéric Roudaut, Annie Floch, Francine Ngani.

This cooperation consists of three years of research work supported by the CELAR (French army), spanning from December 2002 to November 2005. The budget is 190 Keuro. The project's main goal is to develop a well suited methodology and framework for IPv6 related protocols interoperability testing.

7.6. ETSI - Test Specifications for IPv6 Interoperability

Participants: César Viho, Annie Floch.

This contract is a 8-months work supported by the ETSI, spanning from March to September 2005. The budget is of 20 keuro.

The project's main goal was to specify tests using the TTCN3 language for the IPv6 core protocols. The main requirements are listed and corresponding RFCs were also studied leading to main test groups identifications. The final goal is to obtain a framework for testing for interoperability and interoperability test packages for IPv6 Core Protocols.

8. Other Grants and Activities

8.1. National initiatives

8.1.1. ACI "SURE-PATHS"

Participants: Gerardo Rubino, Bruno Sericola, Bruno Tuffin.

We work at the national ACI "SURE-PATHS" whose objective is to provide dependability analysis tools (see http://www-id.imag.fr/Laboratoire/Membres/Sbeity_Ihab/Sure-Paths/firstpage.html for details and for published papers inside the group of participants). This ACI project spans over three years (it started on August 2003).

8.1.2. Point6: IPv6 Skill Cluster

Participants: Laurent Toutain, César Viho.

Point6 has the ambition to bring a support for the various public actors or industriels which wish it. Point6 could help these actors in progressive deployment of IPv6 Internet technologies in their networks which currently work very largely in IPv4, and/or in development of new applications which could draw part of IPv6 technologies, in very diverse fields such as mobile telephony and the personal assistants, house automation, car and intelligent transportation systems, or maybe in unspecified distributed industrial systems for which a better communication between the various parts is required in order to gain in effectiveness or reliability, of the new services of assistance to be brought to residence to the people to reduced capacities, etc.

Period: February 2005 - June 2006

Web site: http://www.point6.net/

8.1.3. G6 / IPv6 Task Force

Participants: Jean-Marie Bonnin, Bernard Cousin, Laurent Toutain, César Viho.

ARMOR actively participates at the G6 (French–speaking IPv6 users group), and on several topics: autoconfiguration, IPv6-IPv4 relations, security (DNSSEC). The G6 project benefits from the regional access point to Renater's IPv6 pilot and to the VTHD network. ARMOR is also very active in the G6test group, which defines tests for IPv6. Our group contributes also to the multicast and the DNSSEC deployment activities promoted by the G6 group.

Web site: http://www.fr.ipv6tf.org/

8.1.4. GDR ASR

Participants: Bernard Cousin, Alexandre Guitton, Miklós Molnár, Joanna Moulierac.

B. Cousin and M. Molnar participate in the ResCom group of the GDR ASR ("Architectures, Systems and Networks") of the CNRS.

Web site: http://www.arp.cnrs.fr/. We can find there the specific contributions of the team in the different deliverables of the corresponding working groups.

8.2. European initiatives

- The project is an active partner of ETSI for interconnection testing in the IPv6 context. See 6.12 and 9.3 for details.
- The project is an active member of EuroNGI Network of Excellence. It has contributed to the deliverables of working packages (Joint Research Activities)

  - WP.IA 6.1: graduated course program,
  - WP.JRA.2.2: Traffic management in a multi-provider context,
  - WP.JRA.5.4: Network optimization and control,
  - WP.JRA.5.5: Numerical, simulation and analytic methodologies,
  - WP.JRA.6.1: Quality of service from the users' perspective and feedback mechanisms for quality control,
  - WP.JRA.6.2: Payment and cost models for NGI.

Web site: http://eurongi.enst.fr/en_accueil.html

8.2.1. Sub-project AUCTION of EuroNGI

Participants: Patrick Maillé, Bruno Tuffin.

We coordinate the AUCTION project funded for 2005 by the network of excellence EuroNGI, to work on inter-domain pricing by means of auctions. We aim at defining the way different ISPs could negotiate exchanges to transport their own traffic (e.g. through a redefinition or generalization of BGP, the Border Gateway Protocol). This work is in collaboration with Prism laboratory (Université de Versailles-St Quentin), The University of Cantalabria, Athens University of Economics and Business, and the University of Roma 2.

8.3. International initiatives

- We work with Duke university (USA) on modelling aided by Petri nets.
- We work with the University of Montreal on the development of randomized Quasi-Monte Carlo methods, with applications in telecommunications.
- We have an ECOS SUD research program with Uruguay, with ARMOR involved in pricing and capacity planning activities.
- We also have obtained a one year funding from INRIA to work with Florida State University on Quasi-Monte Carlo methods and their randomizations, with applications in finance and telecommunications.
- We are currently working with the university of Arizona (M. F. Neuts), with the Indian Institute of Technology, Madras (P. R. Parthasarathy) and AT&T Labs Research (V. Ramaswami) on the analysis of fluid models.
- ARMOR is a partner of the STIC Asia program on IPv6. This program founded by INRIA, CNRS and MAE enhances collaboration between Asian countries (mainly South Korea, Japan and China) and French laboratories to promote research on IPv6 and related protocols. ARMOR is involved in network measurements and mobility.
- In the STIC INRIA - Universities of Tunisia program, we have a common project with ENSI, Tunisia on “Optimization of dynamic wireless networks”.
- R. Marie is a member of the IFIP working groups 6.3 (Performance of Communication Systems) and 7.3 (Computer System Modelling and Performance Evaluation). G. Rubino is a member of the IFIP working group 7.3.

8.4. Associated team “PAIR” (or PAWN: Planning of the Architecture and the infrastructure of a Wide area Network)

Participants: Héctor Cancela (Montevideo, responsible for Uruguay), Franco Robledo, Gerardo Rubino (responsible for France), Bruno Tuffin, María Urquhart (Montevideo), Martín Varela.

PAIR is an associated team, that is, a formal cooperation between two teams, with mainly INRIA funding. It has been started at the end of 2001. PAIR formalizes the cooperation between a subgroup of ARMOR and a subgroup of the Operations Research Team at the Computer Science Department of the Faculty of Engineering, University of the Republic, Montevideo, Uruguay. PAIR also helps in developing our partnership with the ITAM institution at Mexico. The goal of the team is to develop techniques for the design of a WAN (Wide Area Network). From the scientific point of view, this means very complex high-dimensional optimization problems set in terms of graphs, with several other end-to-end aspects including performance, dependability, performability, perceived quality.

For the scientific report on our activities in 2005, see 6.4 and 6.5.

8.5. Visiting researchers

- Adje Assohoum, vice-dean of Mathematics and Computer Science at the Cocody University (Ivory Coast) sojourned during three months in our laboratory to work on new trends in information technologies and multimedia.

- Two master students of the ENSI Tunisian engineering school visited our team for three months in the context of the INRIA INTERNSHIP project. They worked on the implementation of new methods in wireless network simulation.
- Naouel Ben Ali PhD student of the CRISAL laboratory at ENSI, Tunisia worked on the multicast routing optimisation problem with several optimization criteria in our team
- Professor Abdelfettah Belghith, head of the pole RIM at the laboratory CRISTAL of ENSI, Tunisia visited our laboratory in November 2005.

9. Dissemination

9.1. Animation of research activities

- Bruno Tuffin is a member of the "Comité des actions incitatives" for the "Conseil d'Orientation Scientifique et Technologique de l'INRIA" (COST).

9.1.1. Editorial activities

- R. Marie is co–editor of the *Performance Evaluation* journal.

9.1.2. Program committees

- Jean-Marie Bonnin served at the PC of ITST2005 (Intelligent Transportation System Telecommunication), Brest, France, June 2005.
- Bernard Cousin is a member of the Program Committee of "Securité, architecture et réseaux". This is a French workshop held every year on Network Security.
- R. Marie has been a member of the TPC of EPEW'2005 (European Performance Engineering Workshop) and NETWORKING 2005.
- Louis-Marie Le Ny and Bruno Tuffin were PC members of the European Simulation and Modelling Conference (ESM2005), October 24-26, Porto, 2005.
- B. Sericola has been in the PC of ASMTA'05 (12th International Conference on Analytical and Stochastic Modelling Techniques and Applications), June 13-16, Riga, Latvia.
- B. Sericola has been in the PC of MAM'05 (Fifth International Conference on Matrix Analytic Methods in Stochastic Models), June 21-24, Pisa, Italy.
- Bruno Tuffin was PC member of the 5th IEEE International Symposium on Signal Processing and Information Technology (ISSPIT'05), Athens, December 2005.
- R. Marie and G. Rubino served in the Program Committee of QEST'05 (Int. Conf. on Quantitative Evaluation of Systems, Turin, Italy, 2005). QEST is the merge of three previous series: TOOLS (Int. Conf. on Modeling Techniques and Tools for Computer Performance Evaluation), PNPM (Int. Workshop on Petri Nets and Performance Models) and PAPM-ProbMIV (Joint International Workshop on Process Algebras and Performance Modeling and Probabilistic Methods In Verification), that started to run in 2004.
  G. Rubino is co-PC chair of QEST'06 (Riverside, California, Sept. 2005). R. Marie belongs to the PC of QEST'06.
- G. Rubino served in the Program Committee of DSN'05 (Int. Conf. on Dependable Systems and Networks, Yokohama, June 2005).

- G. Rubino served in the Program Committee of EDCC-5 (European Dependable Computing Conf., Budapest, Apr. 2005).
- G. Rubino served in the Program Committee of LANC'05 (Latin America Networking Conference, supported by both ACM et IFIP), Cali, Colombia, September 2005.
- G. Rubino serves in the Program Committee of the following 2006 conferences:
  - ISAS 2006 (3rd International Service Availability Symposium); Helsinki, Finland, May 15-16, 2006;
  - SIGMETRICS/Performance 2006 (Joint International Conference on Measurement and Modeling of Computer Systems), (ACM et IFIP), St Malo, Juin 2006;
  - ICIL'06 (International Conference on Industrial Logistics), Kaunas, Lithuania, 26-29 June 2006;
  - EDDC–6 (6th European Dependable Computing Conference, IEEE et IFIP), Coimbra, Portugal, October 18-20, 2006.

9.1.3. Organisation of meetings

- Bruno Tuffin organized the invited session on rare event simulation at the Winter Simulation Conference, Orlando, December 2005.

9.1.4. Visits

- J–M. Bonnin visited the Seoul National University for ten days.
- B.cousin, J–M. Bonnin and M. Molnár visited the CRISTAL Laboratory of ENSI, Tunisia. Bernard Cousin gave a seminar on his multicast and traffic engineering activities.
- B. Sericola visited the Free university of Brussels as reviewer of the Ph.D. thesis of Ana da Silva Soares on fluid queues.
- G. Rubino visited City University of Hong Kong and the Chinese University of Hong Kong in June 2005, 8 days, for working on stochastic modelling of complex systems.

9.1.5. Participation in seminars, invitations

- B. Tuffin was invited for one week in July at the University of Montreal to work on Quasi-Monte Carlo methods. He gave a lecture at the *Centre de Recherche sur les Transports* (CRT) during this period.
- B. Tuffin gave a lecture on Quasi-Monte Carlo methods at the Advanced Finance Seminar of Florida State University in September.
- G. Rubino and B. Tuffin were invited to give lectures on rare event simulation in May at the University of Amiens.
- G. Rubino gave a seminar on automatic evaluation on perceived quality at a joint workshop by Thomson, Philips and INRIA (AIR & D context), in St Malo, April 26, 2005.
- G. Rubino was invited to give a talk on PSQA (see 6.4) at Philips Eindhoven, May 27, 2005, in a workshop on quality issues.
- G. Rubino was keynote speaker at the 2nd workshop on 'New Paradigms in Interaction Design', organized by the *Telecommunications Research Center* of Vienna and the Austrian Computer Science Society, Vienna, November 2005.
- G. Rubino gave a seminar on the coupling of our PSQA technology and classical modelling techniques for performance evaluation of communication systems at the Chinese University of Hong Kong in June 2005.
- G. Rubino was invited to give a talk on dependability and security analysis at the JSSI workshop organized by the DGA (Defense) at Cesson, November 2005.

9.2. Teaching

9.2.1. Local teaching activities

The team's members have a variety of responsibilities concerning teaching in the local environment (Ifsic, Cnam Rennes, Rennes IUT, Insa, ENST Bretagne, Rennes Mathematics Institute). At the Bac+5 level, B. Cousin, R. Marie, G. Rubino, B. Sericola, C. Viho, L. Toutain, J-M. Bonnin, and D. Ros give different courses in two Masters (in Probability and in Computer science), in the 3rd year of DIIC, and in the ISA DESS, at the Rennes 1 university, at the ENST Bretagne, and at the ENSAI. The main subjects are networking, protocols, dimensioning problems, dependability analysis, etc. C. Viho is in charge of the ISA (computer science and its applications) DESS at the Rennes 1 university. L. Toutain is in charge of the RSIE (networking and information systems for enterprises) master's degree at ENST Bretagne; he also gives networking courses at the ISIA, at Sophia Antipolis.

9.2.2. International teaching activities

- G. Rubino has given a course on network analysis at the Lebanese University of Beyrouth, in the context of a joint doctoral program between this university and other European institutions (January 2005).
- Bernard Cousin is in charge of the coordination of the french side for the DESS NTIM at Cocody university (Abidjan, Ivory Coast).
- J-M. Bonnin and M. Molnar participated to the master thesis formation at ENSI, Tunisia.
- M. Molnar gave a course at the University ENSA, Oujda, Morocco.

9.3. Standardization activities

Participants: Jean-Marie Bonnin, Bernard Cousin, Gilles Guette, Laurent Toutain, César Viho.

The Armor team dedicates a significant effort toward standardization and certification in the telecommunications area. We participate in several working groups of the main telecommunication standardization institutes like the IETF (Internet Engineering Task Force), ETSI (European Telecommunication Standardization Institute), 3GPP (3rd Generation Partnership Project), etc. We are also very active in the main mailing-lists treating new generation networks and protocols. Several proposals of drafts and contributions to the definition of standards and RFCs (Request For Comments) have been published. Our research concerns mainly the IPv6 related protocols, IPv6 mobility (MIPv6), IPv4–IPv6 transition mechanisms such as DSTM (Dual Stack Transition Mechanism), small group multicasting [107], [106] and "Universal Mobile Telecommunications System"(UMTS). We have a long term activity on security issues of network layer mobility: security mechanisms of mobile IPv6, interactions between mobile IPv6 and IPsec/IKE, modern network access control (based on AAA) in a mobile environment, security of the DNS (DNSSEC) and its usage as a large scope PKI, secure two-space solutions for mobility and multi-homing, etc.

We also participated to the RFC 4033 on DNS security (see [9]).

9.3.1. IPv6 Ready Logo Programme

The Armor team has also a major role in the world-wide certification process for IPv6 products launched by the IPv6 Forum, the "IPv6 Ready Logo Programme". For details, see http://www.ipv6ready.org. This project aims to provide the means needed to test existing IPv6 products to be deployed in the market. The Armor team leads the technical part of this Programme by defining the certification process itself, specifying required tests, and developing some of the interoperability tests needed. This work is done together with the IPv6 Forum, the ETSI in Europe, the WIDE-project in Japan and the TTA (Telecommunications Technology Association) in Korea.

9.4. Participation to evaluation of research

G. Rubino was one of the 6 experts that evaluated the PRECEPT “cluster” of research activities at France Telecom R&D (Traffic Modelling, Network Control and Protocol Evaluation), in June 2005, requested by the Scientific Management of the company.

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