INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Team dionysos

Dependability, Interoperability and PerfOrmaNce analYsiS of netwOrkS

Rennes - Bretagne Atlantique

THEME COM

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2. Overall Objectives

2.1. Introduction

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 fulfillment 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, Quality of Experience and performability evaluation).

The DIONYSOS group works on different 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 their different components. 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, at different levels. Concerning the types of networks considered, we mainly work in the wireless area, on Content Delivery Networks for our work around measuring the perceived quality, or QoE, and on some aspects of optical networks. Our work on interoperability concerns IPv6 devices. This testing activity 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. Our team contributes in providing solutions (methods, algorithms and tools) which help in obtaining efficient interoperability test suites for new generation networks. >From the application point of view, we also have activities in pricing methodologies, a critical multi-disciplinary area for telecommunications providers, with many defying open problems for the near future.

Related to the previous elements we have 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 QoE, performance, dependability, performability, QoS, vulnerability, etc.. In particular, we develop techniques to measure in an automatic way the quality of a video or audio communication *as perceived by the final user*. 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.

2.2. Highlights

This year, the international activities of the team exhibited an important development, in three directions. First, our historical cooperation with Uruguay entered a new phase with a change in its dimensions, because a common laboratory (called Cladit) with a larger partnership is being created (more on this in 2008). Second, we boosted the cooperation with the University of Montréal on simulation; Pierre L'Ecuyer spent a sabbatical year with us (see 8.5) and together we started an Associated Team headed by Pierre L'Ecuyer from the Canadian side, and by Bruno Tuffin here. Third, Nizar Bouabdallah spent six months with Professor Boutaba at Waterloo, Canada (see 9.2), consolidating the cooperation on captor networks in both teams.

Voir.

3. Scientific Foundations

3.1. Introduction

Keywords: *IP*, *IPv6*, *Markov chains*, *Monte Carlo techniques*, *QoE*, *QoS*, *Quality of Experience*, *Quality of Service*, *Resource allocation*, *availability*, *congestion control*, *dependability*, *dimensioning*, *discrete event models*, *end-to-end protocols*, *fluid flow models*, *high speed networks*, *interconnection*, *interoperability*, *metrology*, *multimedia*, *network*, *perceived quality*, *performability*, *performance*, *pricing*, *protocols*, *queues*, *reliability*, *reliability*, *simulation*, *stochastic processes*, *testing*, *throughput control*, *traffic control*.

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 it can be seen as an unifying concept in 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.

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 also investigate the impact of network QoS on multimedia payloads to reduce the impact of congestion.

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. We are interested in analyzing these types of flows from this user-oriented point of view. We focus on the *user perceived quality*, the main component of what is nowadays called Quality of Experience (in short, QoE), to underline the fact that, in this case, we want to center the analysis on the final user. We work on the automatic analysis of the QoE, activity that concerns basically CDN (Content Delivery Networks). We develop a project called PSQA, allowing to automatically measuring the QoE.

Another special case to which we devote research efforts in the team is the assessment of qualitative properties related to interoperability testing. This refers to the act of determining if end-to-end functionality between at least two communicating systems is as required by the base standards for those systems. Conformance 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 Labeled Transition Systems). It is an LTS which distinguishes inputs, outputs and internal actions.

3.3. Stochastic modeling

The scientific foundations of our modeling activities are composed of stochastic processes theory and, in particular, Markov processes, queuing theory, stochastic graphs theory, etc., either for developing 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 systems from the classical so-called *call level*, leading to standard models (for instance, queuing ones) and also at the *burst level*, leading to *fluid models*.

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.

Pricing is a good example of a multi-disciplinary research activity half-way between applied mathematics, economy and networking, centered on stochastic modeling issues. Indeed, the Internet is facing a tremendous increase of its traffic volume. As a consequence, real users complain that large data transfers take too long, without any possibility to improve this by themselves (by paying more, for instance). A possible solution to cope with congestion is to increase the link capacities; however, many authors consider that this is not a viable solution as the network must respond to increasing demand (and experience has shown that demand of bandwidth has always been ahead of supply), especially now that the Internet is becoming a commercial network. Furthermore, incentives for a fair utilization between customers are not included in the current Internet. For these reasons, it has been suggested that the current flat-rate fees, where customers pay a subscription and obtain an unlimited usage, 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 can help in improving the management of the network but is a costly option. These are some of the various aspects often present in the pricing problems we address in our work.

4. Application Domains

4.1. Panorama

Keywords: *CDN*, *Extranet*, *Internet*, *Intranet*, *QoE*, *QoS*, *multimedia*, *pricing*, *providers*, *telecommunications*, *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 mobility, ...), and on analysis and dimensioning tools: telecommunications architecture configuration, bottleneck search, resource allocation policies comparison, etc.

We can start by pointing out the PSQA technology we have been developing in the last years (PSQA stands for Pseudo-Subjective Quality Assessment) that allows an automatic and quantitative evaluation of the quality delivered to the user by a network transporting audio or video content. PSQA is accurate (which means that it provides values close to those that would have been obtained using a panel of human observers) and efficient (which means that it can work, if useful or necessary, in real time). It's main application area is in network monitoring: PSQA allows to deploy an auditing system that can continuously analyze the perceived quality (the QoE) at specific points in the network. The other main application area of PSQA is in network control, exploiting the fact that the quality assessment can been done in real time. The first applications of our technique that are currently being explored are in the monitoring and control of networks transporting video flows, with focus on IPTV applications in the context of P2P infrastructures, on networks of mobile terminals, on the properties of the SVC codec and their impact on the QoE.

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, or cellular IP, are also important application domains for our research work.

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 our 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 network architecture (topology) without taking into account the reliability of each component).

5. Software

5.1. Internet Protocols Interoperability Testing Platform

Participants: César Viho, Anthony Baire, Antoine Boutet, Ariel Sabiguero.

We have built a platform with almost all free IPv6 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 built a toolkit for easing executing conformance tests written in TTCN-3. This toolkit is made of a C++ library and of a highly customisable CoDec generator. It allows fast development of external components necessary to execute a test suite (CoDec, System and Platform Adapters), by mixing efficiently and reliably parts that can be generated automatically from the TTCN-3 testsuite and parts that are written manually in C++ and gathered in distinct entities named Codets. The toolkit fixes issues that are not yet covered by ETSI standards while being fully compatible with the existing standard interfaces (TRI & TCI). It has been publicly released under the name T3DevKit and made available under the Apache License. The package includes a fully operational conformance IPv6 test suite for testing the RIPng, DHCPv6 protocols.

We have also started to develop a tool for semi-automatically running interoperability test suites for IPv6. This tool interacts directly with target and reference devices involved in the test for running the scenarios and manages the interconnection between the devices using IEEE 802.1Q VLANs. Depending on resources and needs, test control can be centralised in one single console or done separately on each device. The tool has been used successfully used at the Japanese TAHI IPv6 interoperability event in May 2007.

5.2. 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 behaviors of the modeled 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 behavior 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`.

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 [64], implemented in more than 200 sites. The main designer is Duke University. Our contributions are on Monte Carlo methods. We plan now to increase our participation in the development of this tool.

6. New Results

6.1. Pricing

Participants: Arnaud Delenda, Hélène Le Cadre, 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 or is a way to yield incentives for participation in P2P or ad hoc networks. Our work in the area has focused on two aspects: the design and feasability of pricing schemes first, and more recently the study of the behavior of those pricing schemes in the case of an oligopoly.

We have therefore first looked at different ways to design pricing schemes. In [30] and [49], we have developped several schemes for a RED buffer, where 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. In [24], the use of passive and active measurement tools have been introduced into a simple model, while in [47], threshold-based policies are investigated. A quite different idea is described in [18], where a reliability-dependent scheme is built, assuming that the network is not congested thanks to optic fiber. End-to-end connectivity is then the property of interest.

On the other hand, Vickrey-Clark-Groves (VCG) auction mechanisms are gaining popularity in the networking community to incentivize selfish nodes or domains to forward the traffic of their peers. We have shown in [48] that, in fact, VCG auctions can hardly be applied to those problems. Indeed, if some resource constraints (bandwidth, spectrum, and/or power) are to be taken into account, then computing allocations and prices implies solving optimization problems that are computationally hard for general network topologies. If there are no such resource constraints, then VCG auctions are not *budget-balanced*: the sum of subsidies exceeds the sum of charges paid by traffic senders.

We are currently looking at the case of competition between providers: the impact of this competition has to be carefully analyzed. In [60] (to be presented at Infocom 2008), we have designed a slotted resource allocation game with several providers. Total user demand is therefore split among providers according to Wardrop's principle. Using the characterization of the resulting equilibrium, we prove, under mild conditions, the existence and uniqueness of a Nash equilibrium in the pricing game between providers. We also show that, remarkably, this equilibrium actually corresponds to the socially optimal situation obtained when both users and providers cooperate to maximize the sum of all utilities, this even if providers have the opportunity to artificially reduce their capacities.

6.2. Dependability and extensions

Participants: Gerardo Rubino, Bruno Sericola, Bruno Tuffin.

Monte Carlo methods represent the single tool to solve very large Markov chains [56]. In the context of rare-event simulation, splitting and importance sampling (IS) are the primary approaches to make important rare events happen more frequently in a simulation and yet recover an unbiased estimator of the target performance measure, with much smaller variance than a straightforward Monte Carlo (MC) estimator.

In [26], we provide a guided tour of splitting and Russian roulette techniques, introducing along the way some improvements in the implementation of the multilevel splitting.

A significative part of our activity was on IS. In general, the so-called *zero-variance* estimator, i.e., the estimator yielding the exact (expected) value, can be explicitely expressed, but it cannot be implemented because it requires the knowledge of the value we are looking for. In the more specific Markov context, the zero-variance estimator can be expressed in terms of parameters still unknown in practice, but "closer" to the chain dynamics. Nonetheless, this provides valuable insights about the ideal form of an estimator. All the game is then to adequately estimate the above parameters, from heuristics or learning procedures, which should result in an efficient estimator. During 2007, this has been done in a reliability setting, with Markov models for steady-state [45] or transient [57] analysis, or even with static (time-independent) models thanks to a Markov-like contruction procedure [33].

The accuracy of these estimators has to be maintained as the event becomes more and more rare. In a previous work [66], 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 [31], [59], we discuss and relate all robustness measures of rare event estimators, and also consider higher moments than the usually considered ones (first and second order).

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 approaches, we can benefit from the advantages of both methods: error estimation from MC and convergence speed from QMC. Randomized quasi-Monte Carlo (RQMC) is another class of methods for reducing the noise of simulation estimators, by sampling more evenly than with standard MC. In [27], we show how the *array-RQMC* technique, a randomized QMC method we have previously designed and devoted to the simulation of Markov chains, can be used jointly with splitting and/or IS to construct better estimators than those obtained by either of these methods alone.

We started a collaboration with the INRIA team-project IPSO on the the evaluation of the moments of cumulative reward in Markov models [58]. We studied the convergence of the normalized moments and, based on this convergence, we developed a new algorithm to compute them. We also analyzed these moments and gave a probabilistic interpretation of the quantities arising in the algorithm.

6.3. Core persistence in P2P systems

Participant: Bruno Sericola.

Distributed systems are now both very large and highly dynamic. Peer to peer overlay networks have been proved efficient to cope with this new deal that traditional approaches can no longer accommodate. While the challenge of organizing peers in an overlay network has generated a lot of interest leading to a large number of solutions, maintaining critical data in such a network remains an open issue. In [44], which has been done in collaboration with the Inria Asap team, we obtained results concerning the portion of nodes and frequency one has to probe, given the churn observed in the system, in order to achieve a given probability of maintaining the persistence of some critical data.

6.4. Autoconfiguration in IPv6

Participant: Bruno Sericola.

In [37] we studied, with ENST Bretagne, France Telecom Caen and the INRIA project team ARES, a model for the NAP protocol. NAP is 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 provided. NAP offers a fully distributed solution that uses a link state OSPFv3-like approach to perform prefix collision detection and avoidance. In [37], 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.

6.5. Analytical fluid models

Participant: Bruno Sericola.

Motivated by queuing systems playing a key role in the performance evaluation of telecommunication networks, we analyzed in [23] the stationary behavior of a fluid queue, when the instantaneous input rate is driven by a continuous-time Markov chain with finite or infinite state space. In the case of an infinite state space and for particular classes of Markov chains with a countable state space, such as quasi birth and death processes or Markov chains of the G/M/1 type, we developed an algorithm to compute the stationary probability distribution function of the buffer level in the fluid queue. This algorithm relies on simple recurrence relations satisfied by key characteristics of an auxiliary queuing system with normalized input rates.

In [61], we expose a clear methodology to analyze maximum level and hitting probabilities in a Markov driven fluid queue for various initial condition scenarios and in both cases of infinite and finite buffers. Step by step we build up our argument that finally leads to matrix differential Riccati equations for which there exists a unique solution. The power of the methodology resides in the simple probabilistic argument used that permits to obtain analytic solutions of these differential equations. We illustrate our results by a comprehensive fluid model that we exactly solve.

A crucial property of second order fluid models is the behaviour of the fluid level at the boundaries. In [22], two cases have been considered: the reflecting and the absorbing boundary. This paper presents an approach for the stationary analysis of second order fluid models with any combination of boundary behaviours. The proposed approach is based on the solution of a linear system whose coefficients are obtained from a matrix exponent. A practical example demonstrates the suitability of the technique in performance modeling.

6.6. Interoperability Testing

Participants: Alexandra Desmoulin, Anthony Baire, Antoine Boutet, Ariel Sabiguero, César Viho.

To our knowledge, so far a 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.

In previous work we 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 [63]. This year we have studied input management in interoperability testing. We proved that causal dependencies between inputs and outputs can help in this situation [41]. We have also developed techniques and algorithms using formal methods for automatic interoperability tests generation [42].

We have proposed solutions to some issues regarding the last step of testing activity, where abstract test suites are translated in order to obtain executable test suites that are executed against real implementations. We have proposed virtualization based solutions that deal with test management and trace analysis issues during interoperability testing [51].

On a pragmatic side, we try to validate our solutions for new generation networks, mainly IPv6 related protocols [52]. 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), IPsec, 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 Program” (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 also started in 2006 with stronger requirements.

6.7. Multimedia streaming over 3G Mobile Networks

Participants: Kamal Singh, Gerardo Rubino, César Viho.

The third generation (3G) mobile systems are designed to further enhance the communication by providing high data rates of the order of 2 Mbps. The 3G mobile systems aim to provide varied services, like multimedia, in addition to traditional services like voice call. Services like person-to-person two way video calls or one way video calls, aim to improve person-to-person communication. Entertainment services like gaming, video streaming of a movie, movie trailers or video clips are also supported in 3G. Many more of such services are possible due to the augmented data rates supported by 3G networks and because of the support for Quality of Service differentiation in order to efficiently deliver the required quality for different types of services.

We studied the provisioning of QoS over High Speed Downlink Packet Access (HSDPA), making it suitable for multimedia applications. We used the salient feature of HSDPA that is packet scheduling, to satisfy the QoS requirement of H.264 video streaming applications [55]. We did an extensive case study of H.264 video streaming over HSDPA while testing different schedulers [62]. This study brings also novelty in the fact that it evaluates the impact directly on he quality perceived by the users, thanks to our PSQA tool (see next subsection).

Based on our studies, we proposed a Normalized Rate Guarantee (NRG) scheduler [53], which is an extension of a previous QoS scheduler. Our solution provides the following improvements: there is no deterioration in the video quality when there is an increase in the Best Effort traffic, and it distributes loss rates in a fair way to the users with different rate guarantees.

We also studied congestion control schemes that are suited for video flows. The suitability is determined by the rate stability provided by the rate control algorithm of such schemes. We obtained some surprising results when we studied TCP-Friendly Rate Control (TFRC) over HSDPA [54]. We found that, in the context of HSDPA, the rate stability of TFRC was not necessarily better than that of TCP. This was surprising because it is opposite to what is usually reported over wired links.

We also proposed two strategies to counter the problems caused by wireless losses. First, we designed a loss estimation scheme that could estimate the end-to-end wireless loss probability. Second, we used selective retransmissions to recover the lost multimedia data due to wireless losses. Our results showed that the integrated scheme not only improved the video quality due to the retransmission and recovery of some of the lost video data, but also that the recovery itself was efficient because of the wireless loss estimation.

6.8. QoE (Quality of Experience)

Participants: Gerardo Rubino, Pablo Rodríguez-Bocca, Gildas Fargeas.

We continue the development of the PSQA technology (Pseudo-Subjective Quality Assessment) in the area of Quality of Experience (QoE). PSQA is a method to build a measuring module capable of quantifying the quality of a video or an audio sequence, as perceived by the user, when received through an IP network. PSQA provides an accurate and efficiently computed evaluation of the quality. Accuracy means that PSQA gives values close to those than can be obtained from a panel of human observers, under a controlled subjective testing experiment, following an appropriate norm (which depends on the type of sequence or application). Efficiency means that our measuring tool can work in real time, if necessary. Observe that perceived quality is the main component of QoE.

In 2007 our work focused on the application of our technique to the design of a P2P network for distributing real-time video flows (TV over IP). We made the choice of a structured system, that is, a P2P network with a central control manager. The main reason is that we have the PSQA method allowing to measure the perceived quality in real time, which suggests using its output as feedback information in order to optimally controlling the network. We also chose a multisource approach, to address the main drawback in this type of system, the dynamics of the peers that enter and leave the system continuously. The name multisource refers to the fact that, in our system, a node receives the TV stream from many different peers (sources in this case). Our method allows to split the flow in an arbitrary manner, possibly distributing the load in a way that depends on the types

of the frames (with MPEG-2 or MPEG-4 coding), with an arbitrary amount of redundancy, and reducing the signaling to a negligible volume. For this purpose, our distribution system is based on the properties of pseudo-random generators, which constitutes an original application of these tools (see [50] for details). In [35] and [34] we discuss about the performance of this multisource technique. In [36] some of the optimization aspects of the design of such a P2P network are discussed. As a byproduct of this research effort, we started to work on a monitoring platform for measuring the quality level delivered by a CDN (Content Delivery Network); the first results of this effort (main design decisions) were presented in [40].

We also work on applications of PSQA to the analysis of specific network applications and/or services. In these lines, in [62] we analyze the impact of different scheduling techniques in the context of MPEG-4 video streaming over wireless segments. We also continued the line opened some years ago in where we showed how to couple our quality evaluation technique with standard modeling techniques (in that case, with queueing models for performance evaluation purposes). In [39] we present an example of this kind of coupling in the dependability area (in relation with our P2P project we described above).

6.9. Optical networks

Participants: Nizar Bouabdallah, Bruno Sericola.

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.

We first describe our activities around dimensioning and traffic grooming in this type of networks. The rigid and large routing granularity (i.e. wavelength) entailed by optical technologies can lead to important bandwidth waste [12]. Yet, as WDM technology keeps maturing, there is a bandwidth gap between a wavelength channel's transmission speed (over a Gbit/s) and the capacity requirement of customers' connections. In this regard, increasing research interest is now focusing on the development of new concept of traffic aggregation in optical networks. The objective is eliminating both the bandwidth underutilization and the scalability concerns that are typical of all-optical wavelength-routed networks. To achieve this, we proposed and evaluated a new concept of traffic aggregation in WDM optical networks based on the distribution of the aggregation process [13]. Unlike traditional all-optical networks, which limit the access to a lightpath capacity at the ingress node, we allow lightpath channel sharing among several access nodes. 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. These costs include that of the transceivers required at node level, as well as the number of wavelengths. In other words, the network dimensioning is achieved by evaluating the cross-connect and IP router dimensions as well as the number of wavelengths. To date, it lacks a real methodology to dimension such high-speed networks. In this regard, we developed new models to dimension optical networks considering both ring [14] and arbitrary meshed topologies [15]. Our results show that our proposed aggregation technique can significantly improve the network throughput while reducing its cost.

Our second set of works concern reliability issues. One of the major challenges of optical network operators is ensuring the stringent levels of availability required by their highest-class clients. Indeed, in such environments, the cut of a fiber link can lead to a tremendous traffic loss. In this regard, network survivability becomes a critical concern for operators. To alleviate this, backup resources are used to restore failed connections. These resources are usually shared among several primary connections to improve the network utilization. Generally, the primary connections are considered as equally important when contending for the use of the backup resources. However, this solution is unsuitable from service perspective. Indeed, the quality of service (QoS) required by different clients can be very different because of their diverse services' characteristics. To meet this requirement, we introduce relative priorities among the different primary connections contending for access to the shared-protection paths. We developed analytical models for the proposed priority-enabled scheme considering both $1:N$ [16] and $M:N$ shared-protection schemes [17]. As a key distinguishing feature from

existing literature, we derived explicit analytic expressions for the average availability and service disruption rate for the different priority classes. Based on the elaborated model, we also provided a comprehensive study of the impact of the backup sharability on the network reliability when using the backup reprovisioning scheme.

6.10. Wireless communications

Participants: Fatma Bouabdallah-Othman, Nizar Bouabdallah.

We first describe our work on mobility management. The last few years have seen tremendous growth in the installation of IEEE 802.11 wireless local area networks (WLAN) access points as hotspots in public places to support data communications in general and Internet access in particular. WLAN technology has become widely deployed thanks to its simple and robust contention-based MAC protocol. However, the current widely deployed IEEE 802.11 DCF (Distributed Coordination Function) protocol suffers from inherent unfairness issues. In such networks, the performance of all the competing access nodes are dramatically affected once the bit rate of one station degrades. This anomaly is due to the unfairness behavior of the DCF algorithm. To avoid this, we proposed a new solution based on multiple backoff windows principle [38]. We demonstrated through both analytical models and simulations the efficiency of our proposal. Our results show that the proposed algorithm enables fair bandwidth sharing and increases significantly the total network throughput [20].

Future wireless networks are expected also to provide IP-based coverage and efficient mobility support with end-to-end Quality of Service (QoS) requirements. In our work, we propose a new architecture that supports both mobility and QoS management in wireless MPLS networks. To achieve this, we suggested a new micro-mobility management scheme called Micro Mobile MPLS [28]. 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 neighbor subnet that a 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 as demonstrated in [46].

The above-mentioned advances in wireless communication and embedded computing technologies have lead to the emergence of wireless sensor nodes technology. These pill-sized nodes can be deployed in many domains including health, environment and battlefield monitoring. The major concern with such networks is energy-efficiency, due to the limited capacity of the sensor nodes' batteries [21]. Indeed, once a wireless sensor networks (WSNs) is in place, its lifetime must last as long as possible based on the initially provided amount of energy. In view of this, techniques minimizing energy consumption are required to improve the network lifetime. In order to minimize the energy consumption in WSNs, most previous works focused on energy-aware MAC or routing protocols without paying attention to the impact of the density of reporting nodes on the WSN performances. Indeed, we need to study how the network lifetime evolves with respect to the number of deployed reporting nodes. In [32], we showed that by limiting the reporting tasks of a detected event to a small subset of the sensor nodes instead of using all the sensor nodes in the event area, we can achieve significant energy conservation. Moreover, previous works focused mainly on the energy minimization problems. Whereas, minimizing the energy consumption must be achieved while respecting the specific QoS requirements of sensor applications, such as the maximum tolerable time to report an event, and the required event reliability, etc. To tackle these issues, we studied the energy-latency-reliability tradeoff; our first results are presented in [43].

7. Contracts and Grants with Industry

7.1. IST-Go4IT

Participants: César Viho, Antoine Boutet, Ariel Sabiguero.

We are active members of the IST-Go4IT project, financed by the European Commission under the 6th Framework Programme of the European Research Area. The project started in November 2005 and is ending in April 2008. The project partners are made of 11 organizations coming from Europe, China and Brazil. The objectives of Go4IT are:

- to promote and foster conformance testing oriented validation approach as well as associated technologies such as TTCN3,
- to develop the users community of such an approach,
- to supply a range of executable and freely accessible test services,
- to supply the associated range of support services on a free basis
- to supply complementary commercial services such as certification, or consulting,
- to set-up the environment required to develop a low cost, open and generic solution.

7.2. Anemone

Participants: César Viho, Gerardo Rubino, Nizar Bouabdallah, Kamal Singh, Antoine Boutet.

The Anemone project (Advanced Next gEneration Mobile Open NEtwork) is a IST-STREP (Specific Targeted Research Project) project that started in June 1st, 2006 for a duration of 2 years. The objectives of ANEMONE are:

- to gather and integrate in a single place all the components (i.e. latest standards in wireless access technologies, communication protocols, and applications) necessary to conduct research, development and study the feasibility of deployment of the IPv6 mobility technologies,
- to share the partial experiences the partners of the project have on IPv6 mobility deployment in order to leverage the European IPv6 experience,
- to provide a pan-European IPv6 mobility testbed open to the research and developer communities so that they could test and validate their new applications and services,
- to define procedures and tools to conduct experiments, to gather results, to evaluate the performance and to validate the compliance with IETF standards,
- to gather together a significant number of "real users" coming from different cultural and social populations (students, teachers, ISP customers.).

The Dionysos team is an active member of the Anemone project. We are the leaders of the WP3: Testbed integration and Validation.

7.3. P2Pim@ges

Participants: Gerardo Rubino, César Viho, Nizar Bouabdallah, Kamal Singh, Gildas Fargeas, Pablo Rodríguez.

In the context of our work on QoE and its application to network control, as explained in 6.8, we participate to the DGE project P2Pim@ges, together with three other teams at our unit (ACES, ADEPT, ASAP). We mainly work on two aspects: the design problems associated with unstructured P2P architectures for live video transmission, and the performance evaluation of video transporting P2P networks. The project started in October 2007 and runs for two years.

8. Other Grants and Activities

8.1. Regional Initiatives

Bruno Sericola continues its collaboration with Fabrice Guillemin from France Telecom (Lannion) on the analysis of standard and fluid queues [23].

8.2. National initiatives

8.2.1. ARC RARE

Participants: Gerardo Rubino, Bruno Tuffin.

We coordinate an INRIA cooperative research action on rare event simulation and its various applications. The partners are, at INRIA, the project-teams Aspi, Mathfi, Omega and Mescal, abroad the CWI (The Netherlands), Bamberg University (Germany), and industrials EDF and the DGAC (see http://www.irisa.fr/armor/Rare/). This project spans over two years. It started in January 2006 and finished at the end of 2007.

8.2.2. ARC FRACAS

Participants: Bruno Sericola, Nizar Bouabdallah, Fatma Bouabdallah-Othman, Katy Paroux.

We are part of the INRIA cooperative research action FRACAS (Fiabilité des Réseaux Autonomes de Capteurs et Applications à la Sécurité). The partners are the LRI Paris and the INRIA project-teams ARES, DIONYSOS, REGAL and Grand-Large.This project spans over two years, starting in January 2007.

8.2.3. ARC IFFANY

Participant: Bruno Tuffin.

We are part of the INRIA cooperative research action on InFormAtioN theorY: New challenges and new interdisciplinary tools. The partners are at INRIA, the project-teams Maestro, Trec, Hypercom, Temics, POPS, as well as France Telecom, the University of Avignon, the GET/INT, GET/ENST Bretagne, Eurecom, EPFL and the University of Cyprus (see http://www-sop.inria.fr/mistral/personnel/Eitan.Altman/ifany/). This project spans over two years. It started in January 2006 and finished at the end of 2007.

8.2.4. ANR Télécommnucation WINEM

Participant: Bruno Tuffin.

We are part of the ANR Télécommnication WINEM: WIMAX Network Engineering and Multihoming.
ANR project 2007-2009, in cooperation with Motorola, the GET (INT and ENST Bretagne), MAESTRO project-team at INRIA Sophia-Antipolis, the University of Avignon, the Eurecom institute and France Telecom R&D.

WINEM is dedicated to the Ieee 802.16e standard for Broadband Wireless Metropolitan Access (see http://www.lia.univ-avignon.fr/WiNEM/). This project spans over three years, starting in January 2007.

8.2.5. GDR CNRS ROTJER

Participant: Bruno Tuffin.

We participate to the (CNRS funded) group of discussion ROTJER 2007-2008, on Operations Research and Game Theory for communication networks.

8.3. European initiatives

8.3.1. NoE EuroFGI

Participants: Gerardo Rubino, Bruno Tuffin.

EuroFGI is the follow-up of EUroNGI network of excellence, starting in December 2006. Bruno Tuffin is the INRIA team leader in this project. Gerardo Rubino is a member of its Steering Committee.

The project has contributed to the deliverables of the following working packages (Joint Research Activities):

- 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.

8.3.2. CAP project

Participant: Bruno Tuffin.

We are a member of the CAP project (Competition Among Providers in the access network) within EuroFGI NoE, funded for a period of one year between 2007 and 2008, in collaboration with GET/ENST Bretagne, the University of Rome 2 and the University of Cantabria.

8.3.3. COST initiative ECON@TEL

Participant: Bruno Tuffin.

Bruno Tuffin is the French national delegate and project coordinator for the EU COST Activity IS0605. The goal of ECONTEL is to develop a strategic research and training network linking key individuals and organizations in order to enhance Europeâs competence in the field of telecommunications economics, to support related R&D-initiatives, and to provide guidelines and recommendations to European players (end-users, enterprises, operators, regulators, policy makers, content providers) concerning the provision to citizens and enterprises of new converged broadband and wireless content delivery networks (see http://www.cost.esf.org/index.php?id=233&action_number=IS0605).

8.3.4. Other European collaborations

Participants: Bruno Sericola, Gerardo Rubino.

- We are currently working with the Marie-Ange Remiche and Guy Latouche from the university of Brussels (ULB) on the analysis of stationary fluid queues.
- We also work on second order fluid queues with Miklos Telek (Technical University of Budapest, Ungary), Marco Gribaudo and Daniele Manini (University of Torino, Italy).
- We work on new queueing models (B. Sericola, G. Rubino, with Miklos Telek), coming out of our paper [65]).

For other European cooperations, see our activities in the NoE Euro-FGI above.

8.4. International initiatives

8.4.1. ISAT bilateral collaboration with the University of Auckland (New-Zealand) 2006-2007

Participant: Bruno Tuffin.

We had a *ISAT bilateral collaboration with the University of Auckland (New-Zealand) 2006-2007*, to work on pricing methods in a competitive market.

8.4.2. 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, Pablo Rodríguez, Gerardo Rubino (responsible for France), Bruno Tuffin, María Urquhart (Montevideo), Pablo Rodríguez.

PAIR is an associated team, that is, a formal cooperation between two teams. PAIR is today a self-financed sub-project of both partners. It has been started at the end of 2001. PAIR formalizes the cooperation between a subgroup of DIONYSOS and a subgroup of the Operations Research Team at the Computer Science Department of the Faculty of Engineering, University of the Republic, Montevideo, Uruguay. The main activities developed in PAIR concern WAN (Wide Area Network) design and QoE analysis.

For PAIR activities, see the Web pages: http://www.irisa.fr/armor/PAIR.

8.4.3. Other international activities

- We work with the University of Waterloo (Canada) on wireless mesh and sensor networks.
- We work with Duke university (USA) on modeling aided by Petri nets.
- We work with the University of Montréal (team of Pierre L'Ecuyer) on the development of randomized quasi-Monte Carlo methods, with applications in telecommunications.
- We work with Florida State University on quasi-Monte Carlo methods and their randomizations, with applications in finance and telecommunications.
- We work with Stevens Institute of Technology on pricing issues in telecommunications.
- We work with (and received for two months) Pieter de Boer, from the University of Twente, The Netherlands, on rare event simulation.
- In the STIC INRIA - DGRSRT (Universities of Tunisia) program, we have a common project with TRIO (INRIA) and SUP'COM (Tunisia) on "QoS in wireless sensor networks".

8.5. Visiting researchers

- Pierre L'Ecuyer, professor at the University of Montreal, visited us for several months. He stayed at our group from July 2006 until June 2007. His main research areas are pseudo-random number generators and simulation.

9. Dissemination

9.1. Animation of research activities

9.1.1. International memberships

R. Marie and G. Rubino are members of the IFIP WG 7.3 (Working Group in Computer Performance Modeling and Analysis).

9.1.2. Organization of conferences

- Gerardo Rubino and Bruno Tuffin were co-organizers of an International Workshop on Rare Event Simulation, Nice, May 2007.
- Bruno Tuffin was TPC co-chair of the 1st International Conference on Network Control and Optimization (NET-COOP'07), June 5-7, Avignon, France.
- Bruno Tuffin co-organized the 2nd ARC INRIA's National Days, Rennes, October 1-2, 2007.
- Bruno Tuffin was the Vice-General Chair and local arrangement chair of the Second International Conference on Performance Evaluation Methodologies and Tools (Valuetools'07), October, Nantes, France.

9.1.3. Program committees

- Nizar Bouabdallah was PC member of IEEE GLOBECOM 2007, IEEE Global Telecommunications Conference, Ad-hoc and Sensor Networking Symposium, Novembre 2007, Washington, USA.

Gerardo Rubino served in the Program Committee of the following conferences:

- 8th ICIL (International Conference on Industrial Logistics), March 2008, Neguev, Israel;
- 8th ICOR (International Conference on Operations Research), February 2008, La Habana, Cuba;
- 4th Euro-NGI (Next Generation Internet Networks Design and Engineering for Heterogeneity), April 28–30, 2008, Kraków, Poland, 2008.

Bruno Sericola served in the Program Committee of the following conferences:

- ASMTA'07, 14th International Conference on Analytical and Stochastic Modelling Techniques and Applications, Prague, Czech Republic on 3-6 June 2007.
- MAM6, 6th International Conference on Matrix Analytic Methods in Stochastic Models, Beijing, P. R. China, June 11-14, 2008.
- AlgoTel'07, 9ème rencontres francophones sur les aspects Algorithmiques des Télécommunications, Ile d'Oléron, France, May 2007.

Bruno Tuffin served in the Program Committee of the following conferences:

- 4th Annual IEEE Consumer Communications and Networking Conference "Seamless Consumer Connectivity" (CCNC'07), January 11-13 2007, Las Vegas, Nevada.
- 16th IASTED International Conference on Applied Simulation and Modelling (ASM 2007), August 29-31, 2007, Palma de Mallorca, Spain.
- The 4th International Workshop on Grid Economics and Business Models (GECON 2007), August 28th, 2007, Rennes, France.
- European Simulation and Modelling Conference (ESM2007), October 22-24, 2007, St.Julians, Malta.
- 2nd International Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS'07), October 23-25, 2007, Nantes, France.

9.1.4. Managing 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).

9.2. Participations in seminars, invitations

- N. Bouabdallah spent six months at the University of Wateloo (Canada) as a visiting researcher from February to July 2007.
- B. Sericola was invited to visit the university of Torino (Italy) in May 2007.

9.3. Teaching

9.3.1. Local teaching activities

The team's members have a variety of responsibilities concerning teaching in the local environment (Ifsic, ENST Bretagne, Rennes Mathematics Institute). At the Bac+5 level, N. Bouabdallah, R. Marie, G. Rubino, B. Sericola, C. Viho, give different courses in thwo Masters (in Probability and in Computer science), in the 3rd year of DIIC at the Rennes 1 university, at the ENST Bretagne. The main subjects are networking, protocols, dimensioning problems, dependability analysis, etc. C. Viho is in charge of the 2nd year of the Master in Computer Science at the university of Rennes 1.

9.3.2. International teaching activities

- G. Rubino teaches on Performance Evaluation of Computer Networks at the Lebanease University, at Beirut.

9.4. Editorial activities

- R. Marie is co–editor of the *Performance Evaluation* journal.
- Bruno Tuffin is associate Editor for INFORMS Journal on Computing.

9.5. Standardization activities

Participant: César Viho.

The Dionysos team dedicates a significant effort towards 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), etc. We are also 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 contributions focus today mainly on IPv6 and related protocols such as IPv6 mobility.

9.5.1. IPv6 Ready Logo Program

Participant: César Viho.

Dionysos team has also a major role in the world-wide certification process for IPv6 products launched by the IPv6 Forum, the "IPv6 Ready Logo Program". 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 Program 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.

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