RESEARCH CENTRE

**Rennes - Bretagne Atlantique**

**IN PARTNERSHIP WITH:**

**Ecole Nationale Supérieure Mines-Télécom Atlantique Bretagne Pays de la Loire, Université Rennes 1**

# 2020 ACTIVITY REPORT

# Project-Team DIONYSOS

## Dependability Interoperability and perfOrmance aNalYsiS Of networkS

**IN COLLABORATION WITH: Institut de recherche en informatique et systèmes aléatoires (IRISA)**

**DOMAIN**

**Networks, Systems and Services, Distributed Computing**

**THEME**

**Networks and Telecommunications**

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# Project-Team DIONYSOS

*Creation of the Project-Team: 2009 January 01*

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A1.2.4. – QoS, performance evaluation

A1.2.5. – Internet of things

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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 for 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. protocol testing 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 (QoS), Quality of Experience (QoE) and performability); our activities lie essentially in the latter.

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 on IP networks, at different levels. Concerning the types of networks considered, we mainly work in the wireless area, in particular on sensor networks, on Content Delivery Networks for our work around measuring the perceived quality, the main component of QoE, and on some aspects of optical networks. We also work on the assessment of interoperability between specific network components, which is essential to ensure that they interact correctly before they get deployed in a real environment. 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 network economics methodologies, a critical multi-disciplinary area for telecommunications providers, with many defying open problems for the near future.

For most of previous mentioned problems, our work concerns their quantitative aspects. The quantitative aspects we are interested in are QoE, performance, dependability, performability, QoS, vulnerability, etc. We develop techniques for the evaluation of these different aspects of the considered systems through *models* and through *measurement techniques*. 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 range 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. We are also strongly involved in the use of Machine Learning techniques in many different classes of problems, mainly in networking, and we are also developpers of learning procedures, for instance for specific classes of Neural Networks and/or for different objectives (in Reinforcement Learning, in predicting time series, in graph-based learning tools, etc.)

# 3 Research program

## 3.1 Introduction

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

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

## 3.2 Quality of Service and Quality of Experience

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

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

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

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

## 3.3 Stochastic modeling

The scientific foundations of our modeling activities are composed of stochastic processes theory and, in particular, Markov processes, queuing theory, stochastic graphs theory, etc. The objectives are either to develop numerical solutions, or analytical ones, or possibly discrete event simulation or Monte Carlo (and Quasi-Monte Carlo) techniques. We are always interested in model evaluation techniques for dependability and performability analysis, both in static (network reliability) and dynamic contexts

(depending on the fact that time plays an explicit role in the analysis or not). We look at systems from the classical so-called *call level*, leading to standard models (for instance, queues or networks of queues) and also at the *burst level*, leading to *fluid models*.

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

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

# 4 Application domains

## 4.1 Networking

Our global research effort concerns networking problems, both from the analysis point of view, and around network design issues. Specifically, this means the IP technology in general, with focus on specific types of networks seen at different levels: wireless systems, optical infrastructures, peer-to-peer architectures, Software Defined Networks, Content Delivery Networks, Content-Centric Networks, clouds.

A specific aspect of network applications and/or services based on video or voice content, is our PSQA technology, able to measure the Perceptual Quality automatically and in real time. PSQA provides a MOS value as close as it makes sense to the value obtained from subjective testing sessions. The technology has been tested in many environments, including one way communications as, for instance, in video streaming, and bi-directional communications as in IP telephony, UDP- or TCP-based systems, etc. It has already served in many collaborative projects as the measuring tool used.

## 4.2 Stochastic modeling

Many of the techniques developed at Dionysos are related to the analysis of complex systems in general, not only in telecommunications. For instance, our Monte Carlo methods for analyzing rare events have been used by different industrial partners, some of them in networking but recently also by companies building transportation systems. We develop methods in different areas: numerical analysis of stochastic models, bound computations in the same area, Discrete Event Simulation, or, as just mentioned, rare event analysis. In this last case, we focus on the main Monte Carlo approaches (Importance Sampling, Splitting, Recursive Variance Reduction, etc.) and we are mainly interested in the case of rare events of

"artificial origins" (components' failures, congestion problems) as opposed to natural disasters, that need other specific mathematical tools.

# 5 New software and platforms

## 5.1 New software

### 5.1.1 IPv6 Test Toolkit

**Functional Description:** These test suites are developed using the TTCN-3 environment.

The packages contains the full Abstract Test Suites written in TTCN-3 and the source files for building the codecs and adapters with the help of T3DevKit.

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### 5.1.2 Passive Test Tool

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### 5.1.3 T3DevKit

**Keywords:** IPv6, Conformance testing, TTCN-3

**Scientific Description:** We have built a toolkit for easing executing tests written in the standardized TTCN-3 test specification language. This toolkit is made of a C++ library together with a highly customizable CoDec generator that allows fast development of external components (that are required to execute a test suite) such as CoDec (for message Coding/Decoding), System and Platform Adapters. It also provides a framework for representing and manipulating TTCN-3 events so as to ease the production of test reports. The toolkit addresses issues that are not yet covered by ETSI standards while being fully compatible with the existing standard interfaces: TRI (Test Runtime Interfaces) and TCI (Test Control Interfaces), it has been tested with four TTCN-3 environments (IBM, Elvior, Danet and Go4IT) and on three different platforms (Linux, Windows and Cygwin).

**Functional Description:** T3DevKit is a free open source toolkit to ease the development of test suites in the TTCN-3 environment. It provides:

a CoDec generator (t3cdgen) that automates the development process of the CoDec needed for coding TTCN-3 values into physically transmittable messages and decoding incoming messages a library (t3devlib) that provides an object oriented framework to manipulate TTCN-3 entities (values, ports, timers, external functions...) an implementation of the TRI and TCI standard interfaces default implementations for the system adapter (SA), platform adapter (PA), test management (TM), test logging (TL) and component handling (CH) modules default codecs build scripts for the generation of executable test suites, these are tool-independent and facilitate the distribution of test suite sources

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#### 5.1.4 ttproto

**Name:** Testing Tool Prototype

**Keywords:** Interoperability, Conformance testing, TTCN-3

**Functional Description:** ttproto is an experimental tool for implementing testing tools, for conformance and interoperability testing.

It was first implemented to explore new features and concepts for the TTCN-3 standard, but we also used it to implement a passive interoperability test suite we provided for the CoAP interoperability event held in Paris in March 2012.

This tool is implemented in python3 and its design was influenced mainly by TTCN-3 (abstract model, templates, snapshots, behaviour trees, communication ports, logging) and by Scapy (syntax, flexibility, customisability)

Its purpose is to facilitate rapid prototyping rather than experimentations (rather than production use). We choosed to maximise its modularity and readability rather than performances and real-time considerations.

Now you should have a look at the Features page: https://www.irisa.fr/tipi/wiki/doku.php/testing_tool_prototype:features

**URL:** https://www.irisa.fr/tipi/wiki/doku.php/testing_tool_prototype

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#### 5.1.5 CoAP Testing Tool

**Keywords:** Test, Interoperability, Conformance testing, Plugtests

**Functional Description:** The software helps developers of the CoAP protocol assessing if their implementations (either CoAP clients or CoAP servers) are conformant to protocol specifications, and interoperable with other implementations. It encompasses:

- Coordination of CoAP interoperability tests
- Analysis of CoAP traces & issuing verdicts
- Automation of open source CoAP implementations for based reference interop testing

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#### 5.1.6 ioppytest

**Name:** Interoperability testing

**Keywords:** Interoperability, Conformance testing, CoAP, 6LoWPAN, OneM2M

**Functional Description:** The software is a framework for developing interoperability tests. The interoperability tests help developers of network protocol assessing if their implementations are conformant to protocol specifications, and interoperable with other implementations.

The software already integrates interoperability tests for CoAP, OneM2M and 6LoWPAN The framework provides the following features to the users:

- Coordination of the interoperability tests (enabling remote testing )
- VPN-like connectivity between users' implementations (enabling remote testing )
- Analysis of exchanged network traces & issuing verdicts

- Automation of open source implementations for based reference interop testing

This framework is the evolution of the CoAP Testing Tool (https://bil.inria.fr/fr/software/view/2937/tab)

**URL:** https://gitlab.f-interop.eu/f-interop-contributors/ioppytest

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# 6 New results

## 6.1 Performance Evaluation

**Participants** Raymond Marie, Gerardo Rubino, Bruno Sericola.

**Fluid Queues.** Stochastic fluid flow models and, in particular, those driven by Markov chains, have been intensively studied in the last two decades. Not only they have been proven to be efficient tools to mimic Internet traffic flows at a macroscopic level but they are useful tools in many areas of applications such as manufacturing systems or in actuarial sciences, to cite but a few. We propose in [54] a chapter which focus on such a model in the context of the performance analysis of a potentially congested system. The latter is modeled by means of a finite-capacity system whose content is described by a Markov driven stable fluid flow. We describe step-by-step a methodology to compute exactly the loss probability of the system. Our approach is based on the computation of hitting probabilities jointly with the peak level reached during a busy period, both in the infinite and finite buffer cases. Accordingly, we end up with differential Riccati equations that can be solved numerically. Moreover, we are able to characterize the complete distribution of both the duration of congestion and of the total information lost during such a busy period.

**Tight bounds of performance metrics.** Except in some very special (and important) fundamental models where analytical results are available, the main ways to evaluate the performance or the dependability associated with a queue is to use numerical techniques or simulation. These methods have several drawbacks, and concerning the former, one of them is how to deal with open models accepting an unbounded number of customers. Several years ago, based on results by Semal and Courtois, Muntz, De Souza e Silva and Goyal developed a technique allowing to derive bounds of quantitative metrics on a finite Markovian model, that are particularly tight in case of rare events. These techniques were improved in a few works, including ours, where in particular we showed how to apply them to infinite state models of queues, basically in light traffic conditions. In [52] we describe some ongoing work dealing to new improvements of those procedures, always having as an objective to obtain tight bounds of classic metrics, using more general models, always in a Markovian setting.

**Overview on transient analysis of Markovian models.** Analyzing the transient behavior of a queueing system is much harder than studying its steady state, the difference being basically that of moving from a linear system to a linear differential system. However, a huge amount of efforts has been put on the former problem, from all kinds of points of view: trials to find closed-forms of the main state distributions, algorithms for numerical evaluations, approximations of different types, exploration of other transient metrics than the basic state distributions, etc. In [55] we focus on the first two elements, the derivation of closed-forms for the main transient state distributions, and the development of numerical techniques. The text is organized as a survey, and the main goal is to position and to underline the role of the uniformization technique, for both finding closed-forms and developing efficient numerical evaluation procedures. In some cases, we extend the discussion to other related transient metrics that are relevant for applications.

**Performance evaluation of VoD services in hybrid CDN-P2P systems.** Video on Demand services generate the largest amount of traffic in networks nowadays. In reaction to this, many previous works have proposed integrating Content Delivery Networks (CDNs) and Peer-to-Peer (P2P) networks to satisfy this demand. However, their analytical methods do not consider all the factors that affect the performance of these systems. In [24], we present a novel comprehensive framework, based on a fluid model, to evaluate VoD services over hybrid CDN-P2P systems. The proposed framework considers features of the service (e.g., size, coding-rate and popularity of the video), network attributes (e.g., upload data-rate capacity of servers and peers) and characteristics of the behavior of the users (e.g., sojourn time, cooperativeness and frequency of random-seeks). Our framework allows a system to be evaluated under a wide variety of scenarios in terms of network-cost and Quality-of-Service (QoS) parameters. It is flexible enough to model different resource allocation schemes, including a novel scheme to distribute the upload network capacity. Despite the wide variety of considered factors, our framework is tractable and as accurate as discrete-models based on Markov chains that rely, in general, on simulation for their analysis.

## 6.2 Distributed Systems

**Participants** Yann Busnel, Jérome Henry, Frédérique Robin, Bruno Sericola.

**Probabilistic analysis of population protocols.** The computational model of population protocols is a formalism that allows the analysis of properties emerging from simple and pairwise interactions among a very large number of anonymous finite-state agents. In [21] we studied dissemination of information in large scale distributed networks through pairwise interactions. This problem, originally called rumor mongering, and then rumor spreading, has mainly been investigated in the synchronous model. This model relies on the assumption that all the nodes of the network act in synchrony, that is, at each round of the protocol, each node is allowed to contact a random neighbor. In the paper, we drop this assumption under the argument that it is not realistic in large scale systems. We thus consider the asynchronous variant, where at random times, nodes successively interact by pairs exchanging their information on the rumor. In a previous paper, we performed a study of the total number of interactions needed for all the nodes of the network to discover the rumor. While most of the existing results involve huge constants that do not allow us to compare different protocols, we provided a thorough analysis of the distribution of this total number of interactions together with its asymptotic behavior. In [21], we extend this discrete time analysis by solving a conjecture proposed previously and we consider the continuous time case, where a Poisson process is associated with each node to determine the instants at which interactions occur. The rumor spreading time is thus more realistic since it better corresponds to the real time needed for all the nodes of the network to discover the rumor. Once again, as most of the existing results involve huge constants, we provide a tight bound and an equivalent of the complementary distribution of the rumor spreading time. We also give the exact asymptotic behavior of the complementary distribution of the rumor spreading time around its expected value when the number of nodes tends to infinity.

Previous results are extended in [63] and [64], where we propose and analyze a new asynchronous rumor spreading protocol to deliver a rumor to all the nodes of a large-scale distributed network. This spreading protocol relies on what we call a $k$-pull operation, with $k \geq 2$. Specifically a $k$-pull operation consists, for an uninformed node $s$, in contacting $k-1$ other nodes at random in the network, and if at least one of them knows the rumor, then node $s$ learns it. We perform a thorough study of the total number $T_{k,n}$ of $k$-pull operations needed for all the $n$ nodes to learn the rumor. We compute the expected value and the variance of $T_{k,n}$, together with their limiting values when $n$ tends to infinity. We also analyze the limiting distribution of $(T_{k,n} - E(T_{k,n}))/n$ and prove that it has a double exponential distribution when $n$ tends to infinity. Finally, we show that when $k > 2$, our new protocol requires less operations than the traditional 2-push-pull and 2-push protocols by using stochastic dominance arguments. All these results generalize the standard case of $k = 2$.

We analyse in [61] average-based distributed algorithms relying on simple and pairwise random interactions among a large and unknown number of anonymous agents. This allows the characterization of global properties emerging from these local interactions. Agents start with an initial integer value, and at each interaction keep the average integer part of both values as their new value. The convergence

occurs when, with high probability, all the agents possess the same value which means that they all know a property of the global system. Using a well chosen stochastic coupling, we improve upon existing results by providing explicit and tight bounds of the convergence time. We apply these general results to both the proportion problem and the system size problem.

**Permissionless consensus based on Proof-of-Eligibility.** We propose in [42] a consensus algorithm whose objective is to decide on the same union of proposed values, such that with high probability all the values proposed by the honest nodes belong to the decision. Our algorithm has been designed to cope with an asynchronous and permissionless system. By relying on a proof-of-eligibility, our algorithm is tolerant to an adversary capable of instantaneously corrupting entities. A straightforward application of our algorithm is the design of permissionless distributed ledgers.

**Data streaming and sampling.** Distributed systems increasingly require the processing of large amounts of data, for metrology, safety or security purposes. The on-line processing of these large data streams requires the development of algorithms to efficiently calculate parameters. If elegant solutions have been proposed recently, their approximation is commonly calculated from the inception of the data stream. In a distributed execution context, it would be preferable to collect information only on the recent past (for resource saving or relevancy of most recent information). We therefore consider in our work the sliding window model. This year, we have proposed a complete taxonomy of these techniques, summarized in a survey [15]. Moreover, in a specific study, we propose a family of new sampling techniques that take into account both the sliding window model and the presence of a malicious adversary. Wayne Fuller proposed in 1970 a very ingenious method of sampling with unequal inclusion probabilities. After doing justice to this precursor paper and proposing a fast and simple implementation of it, we completely generalize Fuller's method in order to enable the use of a tuning parameter of spreading. The analytical results of these techniques show the excellent performance of the generalized pivotal approach. This generalization makes the sampling method less predictable and seems appropriate to be protected from malicious attacks when sampling from a stream [27].

**Self-organized UAVs networks.** The use of drones has become more widespread in recent years. Many use cases have developed involving these autonomous vehicles, ranging from simple delivery of packages to complex emergency situations following catastrophic events. The miniaturization and very low cost of these machines make it possible today to create large meshes to ensure network coverage in disaster areas, for instance. However, the problems of scaling up and self-organization must be solved in these use cases. In the last years, we first studied different new requirements for the deployment of unmanned aerial vehicles (UAV) networks involving the use of many drones. Then, we have proposed solutions from distributed algorithms and real-time data processing to ensure quasi-optimal solutions to the raised problems. For instance, in the disaster emergency situation context, we propose VESPA, a distributed algorithm using only one-hop information of the drones, to discover targets with unknown locations and auto-organize themselves to ensure connectivity between them and the sink in a multi-hop aerial wireless network. We prove that connectivity, termination and coverage are preserved during all stages of our algorithm, and we evaluate the algorithm performances through simulations. Comparison with a prior work shows the efficiency of VESPA both in terms of discovered targets and number of used drones [26].

**Blockchain and AI.** Bitcoin system (or Bitcoin) is a peer-to-peer and decentralized payment system that uses a cryptocurrency named bitcoin (BTC) and was released as open-source software in 2009. Unlike fiat currencies, there is no centralized authority or any statutory recognition, backing, or regulation for BTCs. All transactions are confirmed for validity by a network of volunteer nodes (miners) and after that, a collective agreement is recorded into a distributed ledger "Blockchain". The Bitcoin platform has attracted both social and anti-social elements. On the one hand, it is social as it ensures the exchange of values, maintaining trust in a cooperative, community-driven manner without the need for a trusted third party. At the same time, it is anti-social as it creates hurdles for law enforcement to trace suspicious transactions due to anonymity and privacy. To understand how the social and anti-social tendencies in the user base of BTC affect its evolution, there is a need to analyze the BTC system as a network. A first study has explored the local topology and geometry of the network during its first decade of existence.

The characteristics, local and global network properties of the user's graph were analyzed at ten intervals between 2009-2020 with a gap of one year [23]. Afterwards, we have focus on illegal activities using BTC systems. We thus utilize machine learning for identifying these illicit entities and addressed the issue by implementing an ensemble of decision trees for supervised learning. More parameters allow the ensemble model to learn discriminating features that can categorize multiple groups of illicit users from licit ones [36]. The proposed model provided a reliable tool for forensic study. In parallel, we conducted an experiment on a dataset of 1216 real-life entities [22].

We have also contributed to the experimentation of the blockchain in different application contexts, requiring mutual trust on a large scale. Among these experimentations, we can cite the following ones:

- *Financial systems.* We propose an approach to parse and visualize the data of the BTC blockchain in a graph structure and carry out analysis that includes tracking and tracing, address clustering and entity tagging. We also try to find patterns in the data at a macro level to provide insights about the overall system. Thus, these efforts lead to foundation work for an analysis tool for getting insights on the coin flow of any financial system including cryptocurrencies [46].

- *Customer management.* Know-Your-Customer (KYC) is an integral part of the onboarding process of a customer for a company. This process requires independent and tedious verifications of customers' identity documents by the businesses leading to the waste of resources. In this study, we propose a solution where the submission and verification of a customer is done only once, and the results are shared with the businesses which require the information. The proposed system uses a blockchain to record and manage the KYC requests and ensure transparency. The KYC data is verified using machine learning processes to ensure further efficiency in the process, by reducing a significant amount of time spent on verifying the customers [50].

- *Network file systems.* We proposed FileShare – a secure decentralized application framework for sharing files and data provenance. It overcomes the integrity and ownership issues in the existing solutions. Here, a Decentralized Application (dApp) on top of Ethereum is responsible for user's registration and for provenance purposes. Ethereum smart contract is used to govern, manage, and provide traceability and visibility into the history of the shared content from its origin to the latest version. Modify and share operations performed on shared files are recorded separately to the blockchain, ensuring high integrity, resiliency, and transparency [48].

## 6.3 Machine learning

**Participants** Yassine Hadjadj-Aoul, Gerardo Rubino, César Viho, Quang Pham Tran Anh, Ahcene Boumhand, Sid Ali Hamideche, Illyyne Saffar, Anouar Rkhami, Rahali Mohamed, Imane Taibi.

Our activities around Machine Learning tools keeps increasing. We describe them in this sub-section, but observe that some of the topics discussed here could also appear in other parts of the section. Similarly, in previous subsection we describe recent work around blockchains and Machine Learning (Subsection 6.2,page 10) that we preferred to keep together with other activities in distributed systems.

**Evolutionary Actor-Multi-Critic Model.** Recent achievements in Deep Reinforcement Learning (DRL) have shown the potential of this approache to solve combinatorial optimization problems. However, the Deep Deterministic Policy Gradient algorithm (DDPG), which is one of the most effective techniques, is not suitable to deal with large-scale discrete action spaces, which is the case of the Virtual Network Function-Forwarding Graph (VNF-FG) placement. To deal with this problem, we propose several enhancements to improve DDPG efficiency [37]. In order to avoid getting stuck at a local minimum, we propose to multiply the number of critic (for Q-value) neural networks while improving the exploration using a lightweight evolutionary algorithm to make these neural networks evolve, in order to discover better ones. The proposed approach has been applied in the context of the services placement problem and has shown its superiority over conventional methods.

**Machine Learning for correlated time series predictions.** One of the problems where Machine Learning (ML) leads to very good results is in predicting time series values, in many fields of science and technology. We are interested in this area, and in several of its applications, around networking problems. In particular, we developed a methodology called PSQA (Pseudo-Subjective Quality Assessment) for measuring the current Perceived Quality of an application or service built on the Internet around the transportation of audio or video/audio content such as video streaming, IP telephony, etc. PSQA is based on Supervised Learning. It works automatically, in real time if necessary, and it is as accurate as a panel of human observers. We are now working on transforming our tools for *predicting* the Perceived Quality in a close future of present time. Te goal is to make good predictions about how quality will evolve, and tgus being able to take optimal decisions, for instance, in network control. For this extension of PSQA, we precisely need to build time series predictors, and we are exploring them with learning tools close to those used for building our monitoring tool. The keynote [51] present some of the ideas we are following in this research direction.

**Network tomography.** Network tomography is a discipline that aims to infer the internal network characteristics from end-to-end correlated measurements performed at the network edge. Paper [39] presents a new tomography approach for link metrics inference in an SDN/NFV environment (even if it can be exported outside this field) that we called TOM (Tomography for Overlay networks Monitoring). In such an environment, we are particularly interested in supervising network slicing, a recent tool enabling to create multiple virtual networks for different applications and QoS constraints on a Telco infrastructure. The goal is to infer the underlay resources states from the measurements performed at the overlay structure. We model the inference task as a regression problem that we solve following a Neural Network approach. Getting labeled data for the training phase can be costly, but our procedure generates artificial data for the training phase. By creating a large set of random training examples, the Neural Network learns the relations between the measures done at path and link levels. Generating artifical data has the advantage that we can cover the borders of the ranges of the considered metric, thus helping to obtain a good accuracy in the answer. This approach takes advantage of efficient Machine Learning solutions to solve a classic inference problem. Simulations with a public dataset show very promising results compared to statistical-based methods. We explored mainly additive metrics such as delays or logs of loss rates, but the approach can also be used for non-additive ones such as bandwidth.

**Inference of performance metrics from Web-based measurements.** Web browsing remains one of the dominant applications of the internet, so inferring network performance becomes crucial for both users and providers (access and content) so as to be able to identify the root cause of any service degradation. Recent works have proposed several network troubleshooting tools, e.g, NDT, MobiPerf, SpeedTest, Fathom. Yet, these tools are either computationally expensive, less generic or greedy in terms of data consumption. In [44], we suggest leveraging passive measurements freely available in the browser and Machine Learning (ML) techniques to infer network performance (e.g., delay, bandwidth and loss rate) without the addition of new measurement overhead. To enable this inference, we propose a framework based on extensive controlled experiments where network configurations are artificially varied and the Web is browsed. Then, ML is applied to build models that estimate the underlying network performance. In particular, we contrast classical ML techniques (such as Random Forests) to Deep Learning models trained using fully connected Neural Networks and Convolutional Neural Networks (CNNs). Results of our experiments show that the latter have a higher accuracy compared to classic ML approaches. Furthermore, the model's accuracy improves considerably using CNNs. In [43], we develop and implement our approach, and compare its estimation accuracy with the most known web-based network measurement techniques available nowadays. We follow a controlled experimental procedure to derive our inference models. The results show that our method can give a very good accuracy compared to others, its accuracy is even higher than most standard techniques, and very close to that of the rest of them.

**Monitoring with Machine Learning.** The use of artificial intelligence techniques in monitoring is becoming an essential building block for the new techniques developed in recent years. In this context, we proposed three applications in different use cases.

- Multilabel scene classification has emerged as a critical research area in the domain of remote sensing. Contemporary classification models primarily emphasize on a single object or multiobject scene classification of satellite remote sensed images. These classification models rely on feature engineering from images, deep learning, or transfer learning. Comparatively, multilabel scene classification of Very High Resolution (VHR) images is a fairly unexplored domain of research. Models trained for single label scene classification are unsuitable for the application of recognizing multiple objects in a single remotely sensed VHR satellite image. To overcome this research gap, the current inquiry proposes to fine-tune state of the art Convolutional Neural Network (CNN) architectures for multilabel scene classification. The proposed approach pre-trains CNNs on the ImageNet dataset and further fine-tunes them to the task of detecting multiple objects in VHR images. To understand the efficacy of this approach, the final models are applied on a VHR data base: the UCMERCED image dataset containing 21 different terrestrial land use categories with a submeter resolution. The performance of the final models is compared with the graph convolutional network-based model by Khan et al. From the results on performance metrics, it was observed that the proposed models achieve comparable results in significantly fewer epochs [20].

- Cough is a symptom in over a hundred respiratory diseases, including Covid-19. The audio features in cough signals contain erudition about the predicament of the respiratory system. Using deep learning or signal processing, these features can be used to build an effective disease prediction system. However, cough analysis remains an area that has received scant attention from machine learning researchers. This can be attributed to several factors such as inefficient ancillary systems, high expenses in obtaining datasets, or difficulty in building classifiers. In [19], we categorize and review the current progress on cough audio analysis for the classification of pulmonary diseases. We also explore potential future research issues. Additionally, we propose a model for the classification of ten serious pulmonary ailments commonly seen in Indian adolescents. The proposed model is evaluated against four existing state of the art techniques in the literature.

- The electricity grid is evolving to a distributed infrastructure in which smart grids integrating renewable energies will become dominant. Because of the limited capacity of the battery to store the energy produced at certain time of the day, it is necessary to shift the consumption to when the electricity is actually produced. This study deals with the estimation of solar panel production in order to forecast when and how much electricity will be available. We propose an Artificial Neural Network model to predict the hourly production of photovoltaic (PV) plants. We evaluate our approach over a large dataset of solar panel electricity production over a period of seven years [45].

## 6.4 Future networks and architectures

**Participants** Yassine Hadjadj-Aoul, Yann Busnel, Gerardo Rubino, Sofiene Jelassi, Ghina Dandachi, Quang Pham Tran Anh, Rahali Mohamed, Anouar Rkhami, Soumaya Kaada, Amine Rguez, Imane Taibi.

**Cache placement.** Dealing with the ever-increasing video traffic is certainly one of the major challenges facing Internet Service Providers (ISPs). In this context, the strategic placement of caches is seen as one of the most important remedies, especially with recent advances in the field of virtualization. Unlike the existing works, which only focus on the placement issue, we also consider the problem of determining the optimal amount of cache to place at each possible location. We formalize, in [14], the problem of caches placement as a multi-objective optimization problem, in which we minimize both the average distance from which contents are retrieved and the peering links utilization. As the proposed problem is NP-hard, we propose to solve it using the Greedy Randomized Adaptive Search Procedure (GRASP) meta-heuristic. Simulations results reveal the quality of the obtained solutions compared to an exhaustive search method. At the same time, they reveal that the solution is not to put all resources at the edge or at the core, as some studies claim, but to partition them judiciously, which mainly depends on the objectives of the ISPs.

**Anomaly Localization.** Source routing represents a good opportunity to enhance monitoring solutions, particularly probing techniques. This technique allows deploying customized probing schemes to fulfill different monitoring needs like troubleshooting or Service Level Agreement (SLA) supervision. In this context, the use of probing cycles is a promising monitoring method. The deployment of such probing schemes becomes easier thanks to source routing since it allows constraining the traffic to follow specific paths. In [38] we propose the FEAL monitoring framework (Framework for Efficient Anomaly Localization) based on source routing probing cycles. The framework is mainly composed of two parts: the *Probing Cycles* and the *Anomaly Detection* modules. The first one defines the probing strategy by deploying the needed monitors and finding the probing cycles to cover the network topology. The *Anomaly Detection* module is based on our previously proposed (end of 2019) statistical algorithm for the inference of link metrics named ESA (Evolutionary Sampling Algorithm), here extended to more general classes of metrics. We prototyped and evaluated the FEAL framework with a P4 implementation of source routing over a Mininet emulator. The results show that our framework detects and localizes efficiently the failure points in the network.

**Machine learning for network slicing.** Resource allocation of 5G and beyond 5G (B5G) network slices is one of the most important challenges for network operators. Network slicing mainly consists in placing constrained services, which are typically expressed in the form of a Virtual Network Function-Forwarding Graph (VNF-FG). Several solutions have already been proposed in the literature to address these types of problems. However, in these approaches, past placement experiences yield no benefit to new placements (i.e., noting is learnt from the obeserved past).

In [25], we leverage one of the most advanced techniques in Deep Reinforcement Learning (DRL) in order to efficiently solve the placement of complex and constrained services problem. In particular, we have proposed an extension of this approach in order to better explore the space of solutions while making them safer. The experimental platform we have developed, which is based on Mininet and containers, allows us to show the advantage of our method over existing ones.

In [41], we unveil the potential of Graph Convolutional Neural (GCN) networks and Deep Reinforcement Learning techniques in solving the services' placement problem. The key point of our approach is modeling the placement problem as an episodic Markov Decision Process which is solved in a Reinforcement Learning fashion using a GCN-based neural architecture. The simulation results highlight the efficiency of our approach through an increased performance over time, while outperforming state-of-art solutions in terms of the services' acceptance ratio.

Due to the exploration-exploitation dilemma, the solutions obtained by DRL-based approaches can be infeasible. This can lead to reliability concerns. To overcome this issue, we combine, in [40], DRL and relational Graph Convolutional Neural (GCN) networks in order to automatically learn how to improve the quality of heuristics in the placement of services. Simulation results show the effectiveness of our procedure. Starting with an initial solution given by the heuristics it can find an improvement of about 35% on average.

## 6.5 Wireless Networks

**Participants** Soraya Ait-Chellouche, Yann Busnel, Yassine Hadjadj-Aoul, Ali Hodroj, Bruno Sericola, César Viho.

**Access Control in IoT Networks.** Driven by various services and applications, Machine Type Communications (MTC) will become an integral part of our daily life over the next few years. Meeting the ITU-T requirements, in terms of density, battery longevity, coverage, price, and supported mechanisms and functionalities, Cellular IoT, and particularly Narrowband-Internet of Things (NB-IoT), is identified as a promising candidate to handle massive MTC accesses. However, this massive connectivity would pose a huge challenge for network operators in terms of scalability. Indeed, the connection to the network in cellular IoT passes through a random access procedure and a high concentration of IoT devices would, very quickly, lead to a bottleneck. The latter procedure needs, then, to be enhanced as the connectivity would be considerable. With this in mind, we propose, in [16], to apply the access class barring (ACB) mechanism to regulate the number of devices competing for the access. In order to derive the blocking

factor, we formulate the access problem as a Markov decision process that we were able to solve using one of the most advanced deep reinforcement learning techniques. The evaluation of the proposed access control, through simulations, shows the effectiveness of our approach compared to existing techniques such as the adaptive one and the Proportional Integral Derivative (PID) controller. Indeed, it manages to keep the proportion of access attempts close to the optimum, despite the lack of accurate information on the number of access attempts.

**Enhancing dynamic adaptive streaming over HTTP for multi-homed users.** Nowadays, multimedia streaming traffic reaches 71% of the mobile data traffic over the world and most of the multimedia services use Dynamic adaptive streaming over HTTP (DASH) to adjust video delivery to the dynamic network environment and achieve higher user Quality of Experience (QoE) levels. Moreover, 90% of the video traffic is consumed by smart devices equipped with multiple network interfaces (Wifi, 3G, and 4G) known as multi-homed devices. In [32], we propose a new DASH-parallel streaming solution, which exploits the diversity of access network connections to improve video quality over DASH protocol. Experimental results show that our mthod improves the perceived QoE in different network conditions, without requiring further energy expenditure.

**Vehicular networks.** Road traffic management experts are constantly striving to develop, implement and test a number of novel strategies to reduce traffic congestion impact on the economy, society and the environment. Despite their efforts, these strategies are still inefficient and a call for advanced multidisciplinary approaches is needed. In reaction to this, we introduce in [29] an original traffic congestion mitigation strategy inspired from a well-known technology in wireless communications, i.e. cognitive radio technology. Our strategy exploits Connected Vehicles technology along with the often under-utilized reserved lanes, such as bus and carpool lanes, to virtually inflate the road network capacity to ease traffic congestion situations. Two variants of our strategy have been evaluated using simulation and the obtained results are very promising in terms of the achieved reduction in average travel time for different vehicle classes, including public transportation.

**Indoor localization with FTM.** Multidimensional Scaling is commonly used to solve multi-sensor location problems. In this work, we show that such a technique provides poor results in the case of indoor location problems based on 802.11 Fine Timing Measurements, especially when the number of anchors is small. We then propose an iterative approach based on geometric resolution of angle inaccuracies. We show that this geometric approach provides better location accuracy results than other Euclidean Distance Matrix techniques based on Least Square Error logic. We also show that the proposed technique, with the input of one or more known points, can allow a set of fixed sensors to auto-determine their position on a floor plan [31].

## 6.6 Network Economics

**Participants** Bruno Tuffin, Patrick Maillé, Ximun Castoreo.

The general field of network economics, analyzing the relationships between all acts of the digital economy, has been an important subject for years in the team.

In an ad hoc network, accessing a point depends on the participation of other, intermediate, nodes. Each node behaving selfishly, we end up with a non-cooperative game where each node incurs a cost for providing a reliable connection but whose success depends not only on its own reliability investment but also on the investment of nodes which can be on a path to the access point. Our purpose in [34] is to formally define and analyze such a game: existence of an equilibrium output, comparison with the optimal cooperative case, etc.

In 2020, we still have had a particular focus on network neutrality issues, but trying to look at them from original perspectives, and investigating so-called grey zones not yet addressed in the debate.

**Heterogeneity of neutrality rules.** Network neutrality has recently been repealed in the United States, leading to a worldwide Internet with different imposed policies. We build and analyze in [58]

a game-theoretic model representing the interactions between users, network providers and content providers in this heterogeneous regulation context, and investigate the impact of two neutrality relaxation policies in a part of the world on all actors, compared with a fully-neutral network. Our results show that neutrality repeal may only favor the ISP in the differentiation-authorized zone, but no other actor, and that it can be worse off for everybody if the regulation procedures are very strict in the neutral area. This issue is also discussed in [69].

**A different implementation of Neutrality?** Given the complexity of implementing neutrality, we model and discuss in [33] a quite recent option which could be seen as a trade-off between neutrality and differentiation operated by Internet service providers (ISPs), and satisfy both ends of the world: differentiation potentially chosen by end users. By using a model from the literature, we compare the outcomes of three scenarios: neutrality, non-neutrality with differentiation decided by ISPs, and non-neutrality decided by users. We illustrate that, depending on network parameters, letting end users decide may end up as a fair and viable solution, and that non-neutrality imposed by ISPs is not necessarily bad for all actors.

**Monitoring neutrality.** Compliance to neutrality rules has to be checked thanks to specific measurement tools. Our paper [28] aims at highlighting the weaknesses of current Network Neutrality measurement tools and at providing hints on challenges to be addressed on the topic.

## 6.7 Monte Carlo

**Participants** Bruno Tuffin, Gerardo Rubino.

We maintain a research activity in different areas related to dependability, performability and vulnerability analysis of communication systems, using both the Monte Carlo and the Quasi-Monte Carlo approaches to evaluate the relevant metrics. Monte Carlo (and Quasi-Monte Carlo) methods often represent the only tool able to solve complex problems of these types.

This year, we published the book of selected papers from talks at the 13th International Conference in Monte Carlo & Quasi-Monte Carlo Methods in Scientific Computing (MCQMC) we organized in Rennes in 2018 [53].

**Randomized Quasi-Monte Carlo for quantile estimation.** We consider the problem of estimating the $p$-quantile of a distribution when observations from that distribution are generated from a simulation model. The standard estimator takes the $p$-quantile of the empirical distribution of independent observations obtained by Monte Carlo. As an improvement, we use in [35] conditional Monte Carlo to obtain a smoother estimate of the distribution function, and we combine this with randomized quasi-Monte Carlo to further reduce the variance. The result is a much more accurate quantile estimator, whose mean square error can converge even faster than the canonical rate of $O(1/n)$.

**Gradient-based optimization and sensitivity analysis.** Stochastic gradient estimation plays a central role in gradient-based optimization and sensitivity analysis. We propose in [62] a new unbiased stochastic gradient estimator for a family of stochastic models with uniform random numbers as inputs. By extending the generalized likelihood ratio (GLR) method, the proposed estimator applies to discontinuous sample performances with structural parameters without requiring that the tails of the densities of the input random variables go down to zero smoothly. By overcoming this limitation, our new estimator greatly expands the applicability of the GLR method, which we demonstrate for several general classes of uniform input random numbers, including independent inverse transform random variates and dependent input random variables governed by an Archimedean copula. We show how the new derivative estimator works in specific settings such as density estimation, distribution sensitivity for quantiles, and sensitivity analysis for Markov chain stopping time problems, which we illustrate with applications to statistical quality control, stochastic activity networks, and credit risk derivatives.

**Rare event simulation of regenerative systems.** Rare events occur by definition with a very small probability but are important to analyze because of potential catastrophic consequences. In [30], we consider the estimation of the distribution of the hitting time to a rarely visited set of states for a regenerative process. In a previous paper, we provided two estimators that exploited the weak convergence of the hitting time divided by its expectation to an exponential as the rare set becomes rarer. We now add three new estimators, based on a corrected exponential, a gamma, and a bootstrap approach, the last possibly providing less biased estimators when the rare set is only moderately rare. Numerical results illustrate that all of the estimators perform similarly. Although the paper focuses on estimating a distribution, the ideas may also be applied to estimate risk measures, such as a quantile or conditional tail expectations.

# 7 Bilateral contracts and grants with industry

## 7.1 Bilateral contracts with industry

### 7.1.1 Common Lab INRIA - Nokia

Gerardo Rubino is the coordinator of the research action “Analytics and machine learning”, between Nokia Bell Labs and INRIA. The objective is to carry out common research on an integrated framework for 5G, programmable networks, IoT and clouds that aims at statically and dynamically managing and optimizing the 5G infrastructure using, in particular, Machine Learning techniques. The project ivolves several teams in INRIA and involves the work of several PhD students.

## 7.2 Bilateral grants with industry

### 7.2.1 Cifre on Automation for beyond 5G Mobile Networks, with Nokia

**Participants** César Viho.

Our goal in this Cifre contract 2020–2023 including a PhD thesis supervision (PhD of Sid Ali Hamideche) done with Nokia Bell Labs (Nozay) and IRISA is to focus on designing automatic user profiling based on artificial intelligence and machine learning.

### 7.2.2 Cifre on Resiliency as a Service for 5G, with Nokia

**Participants** Sofiene Jelassi, Gerardo Rubino.

This is a Cifre contract 2020–2023 including a PhD thesis supervision (PhD of Soumaya Kaada), done with Nokia (Paris-Saclay), about Resiliency as a Service for 5G networks using Machine Learning. It concerns providing on demand and evolving resiliency schemes over 5G network using advanced Machine Learning algorithms. It relies on a highly flexible network infrastructure supporting both wired and wireless programmable data planes through a highly-efficient distributed network operating system.

### 7.2.3 Cifre on availability-aware NFVs placements, with Exfo

**Participants** Yassine Hadjadj-Aoul, Gerardo Rubino.

This is a Cifre contract 2020–2023 including a PhD thesis supervision (PhD of Amine Rguez), done with Exfo (Rennes), about availability-aware NFVs placements of network services, using Deep Reinforcement Learning. The objective of the thesis is to exploit the potential of Deep Learning, and more particularly, of Deep Reinforcement Learning, in order to guarantee the high availability of placed network services.

#### 7.2.4 Cifre on multi-task learning, with Orange

**Participants** Yassine Hadjadj-Aoul, César Viho.

This is a Cifre contract 2020–2023 including a PhD thesis supervision (PhD of Ahcene Boumhand), done with Orange Labs (Rennes) and IRISA, on multi-task learning for the discovery of home contexts. The objective of the thesis is to propose and implement a new solution to discover several home context information by exploiting and classifying home data with a unique model based on multi-tasking learning.

#### 7.2.5 Cifre contract on FTM efficiency, with Cisco

**Participants** Yann Busnel.

This is a Cifre contract 2019–2022 including a PhD thesis supervision (PhD of Jerome Henry), done with Cisco (US)co-supervised with the Adopnet and OCIF teams. The objective of the thesis is to propose and implement a new solution to FTM efficiency for indoor location.

#### 7.2.6 Cifre on Cognitive Autonomic Networks in 5G, with Nokia

**Participants** César Viho.

This is a Cifre contract 2017–2020 including a PhD thesis supervision (PhD of Illyyne Saffar), done with Nokia, on the proposition to use machine learning and data analytics to transform user and network data into actionable knowledge which in turn can be automatically exploited by Autonomic Networking approaches for cognitive self management of the 5G network.

# 8 Partnerships and cooperations

## 8.1 International initiatives

### 8.1.1 Inria international partners

**Informal international partners**

- G. Rubino works with Alan Krinik from Cal Poly, Pomona, US, on transient analysis of Markovian models.
- G. Rubino collaborates with S. Basterrech from the VSB-Technical University of Ostrava, Czech Republic, on Machine Learning problems, these days on time series prediction using Reservoir Computing techniques.
- Bruno Sericola works with Marie-Ange Remiche from the university of Namur, Belgium, and with Fabrice Guillemin from Orange Labs in Lannion, France, on the analysis of fluid queues.
- Yann Busnel has taken part in several events to develop Indo-French collaborations, notably within the framework of Campus France. In particular, he led the partnership ith VJTI Mumbai and co-organized the Indo-French Seminar on Artificial Intelligence in Bordeaux in October 2020.
- Yann Busnel works with Dhiren Patel from VJTI, Mumbai, India, on Blockchain and cybersecurity.

### 8.1.2 Participation in other international programs

**Ecos Sud program: project "Masc"**

- Title: Mathematical Algorithms for Semantic Cognition
- International Partner (Institution - Laboratory - Researcher):
  - Universidad de la República (Uruguay) - Biophysics - Eduardo Mizraji, Jorge Graneri
  - Universidad de la República (Uruguay) - Computer science - Pablo Rodríguez-Bocca
- Duration: 3 years
- Start year: 2018
- MASC is a three-year project (code U17E03) with the Faculty of Sciences of the university of the Republic, in Uruguay, on the application of mathematical modeling tools to a better understanding of a cognitive disease called semantic dementia. This involves Prof. Eduardo Mizraji and Jorge Graneri, a PhD student whose co-advisors are Prof. Mizraji and G. Rubino from Dionysos, plus Pablo Rodríguez Bocca, from the Engineering Faculty of the university of the Republic. Our contribution to this project is around the use of mathematical tools applied to the analysis of cognition pathologies.

**Math AmSud program: project "RareDep"**

- Title: Rare events analysis in multi-component systems with dependent components
- International Partner (Institution - Laboratory - Researcher):
  - Universidad Adolfo Ibañez (Chile) - Faculty of Engineering and Sciences - Javiera Barrera
  - Universidad de la República Uruguay (Uruguay) - Computer Science - Héctor Cancela
  - Universidade Federal de Pernambuco (Brazil) - Mathematics - Pablo Martín Rodríguez
- Duration: 2 years
- Start year: 2019
- See also: http://mansci-web.uai.cl/raredep/RareDep/Welcome.html
- The RareDep project focus on developing new techniques addressing two central elements for the improvement of the available tools for risk analysis of complex systems. One is the case of rare events, occurring both in performance and in dependability evaluation of systems modeled as made of many components. Rare events preclude the use of Monte Carlo techniques when the event of interest has a small probability of occurring, and specific methods are necessary, with many open problems in the area. Independence is the usual assumption when building models (more precisely, in almost all works in the field make this assumption), but we know that the assumption is almost never satisfied. We often are constrained by the necessity of assuming independent components in order to be able to use the available methods. In RareDep, we intend to address both problems simultaneously. This needs to develop new variance reduction techniques, for instance in the Importance Sampling family, or in the Splitting one, to be able to exploit data concerning dependencies between the components of the models. This will be built on top of our accumulated experience in the Monte Carlo area (and related fields, such as Quasi-Monte Carlo, numerical integration, etc.), and a starting effort to begin the exploration of what happens when we relax the omnipresent independence hypothesis. We will also explore what happens if we consider new ideas (several coming from the participants of the proposal) for defining new metrics in some specific areas. In these cases, everything is to be done: procedures to deal with rare events, modeling techniques to deal with dependencies between the system's components, and then, both issues at the same time. Our main application area will concern different types of modern networks (in communications, or in energy distribution, for instance).

**Semantic AmSud program: project “ACCON”**

- Title: Algorithms for the Capacity Crunch problem in Optical Networks
- International Partner (Institution - Laboratory - Researcher):
  - Universidad de la República Uruguay (Uruguay) - Computer Science - Héctor Cancela
  - UTFSM (Chile) - Télématica - Reinaldo Vallejos
  - Universidad de Valparaiso (Chile) - Computer Science - Marta Barría
- Duration: 2 years
- Start year: 2019
- See also: http://accon.elo.usm.cl/
- The rapid increase in demand for bandwidth from existing networks has caused a growth in the use of telecommunications technologies, especially WDM optical networks. So far, communication technologies have been able to meet the bandwidth demand. Nevertheless, this decade researchers have anticipated a coming “Capacity Crunch” potential problem associated with these networks. It refers to fact that the transmission capacity limit on optical fibers is close to be reached in the near future. It is then urgent to make the current network architectures evolve, in order to satisfy the relentless exponential growth in bandwidth demand. In other words, the performance bottleneck for optical infrastructures is concentrated around this limiting situation, and the most efficient way of preparing the future of these fundamental technological systems that support the backbone of the Internet is to focus on solving the related management problems. In the previously described scientific context, the ACCON project has a main scientific goal: the development of new strategies capable to provide better resource management techniques to face the threat of the Capacity Crunch. To this end, we will explore the utilization of different analytical techniques to evaluate the performance of several network architecture paradigms, in order to assess their viability in the near future. This will provide us the needed insight leading to finding new strategies for efficiently managing the network resources, and consequently, to contribute addressing this coming Capacity Crunch problem.

#### 8.1.3 Visits of international scientists

- Pranav Nerurkar
  - Date: *(03/2020)* - *(08/2020)*
  - Institution: VJTI Mumbai (India)
  - Supervisor: Yann Busnel

#### 8.1.4 Visits to international teams

**Research stays abroad** Yann Busnel has been hosted as an Invited professor at VJTI Mumbai and IISc Bangalore (India), February 2020

### 8.2 National initiatives

#### 8.2.1 IRT B-Com

Yassine Hadjadj-Aoul, Sofiene Jelassi and Gerardo Rubino are participating at 20% of their time to the IRT B-Com granted by the ANR.

#### 8.2.2 Interregional "ONCOSHARe" project

Yann Busnel is member of the ONCOSHARe Project: ONCOlogy big data SHAring for Research, funded by both Brittany and Pays de la Loire regions (2018–2020). The latter relies on the Inter-regional Network of Clinical Data Centers of the Grand-Ouest.

The main objective of the ONCOSHARe (ONCOlogy big data SHARING for Research) project is to demonstrate, through multidisciplinary cooperation within the West Cancer Center, the feasibility of building a big data in common and patient-centered cancerology and to evaluate its added value for the conduct of in-silico studies. The scientific and technical program of the project consists of 3 main tasks: *(i)* Data sharing and governance; *(ii)* Big data management and processing and *(iii)* Scenario and evaluation of pilot studies.

The project will propose a new governance allowing the multi-domain integration of data and its sharing, which can meet the needs of users while respecting ethical, regulatory and ethical constraints. The innovations resulting from the ONCOSHARe project will be shared within the partners and beyond. The technical results will make it possible to provide new services implementing processing on big data in oncology.

#### 8.2.3 ANR "INTELLIGENTSIA"

Soraya Ait-Chelouche, Yassine Hadjadj-Aoul, Patrick Maillé and Gerardo Rubino are members of the ANR INTELLIGENTSIA: INTelligent Edge using Learning Loops & Information GEneration for NeTwork State Inference-based Automation, 2020-2024 (ANR-20-CE25-0011-03).

The Intelligentsia project aims at (1) specifying novel media access protocols and resources sharing policies to be able to support network slicing for IoT access networks in general, and LoRa networks in particular; (2) designing of a network automation framework that incorporates novel learning algorithms to configure the IoT access network.

#### 8.2.4 IPL (Inria Project Lab) "BetterNet"

Yassine Hadjadj-Aoul, Gerardo Rubino and Bruno Tuffin are members of the IPL (Inria Project Lab) BetterNet: An Observatory to Measure and Improve Internet Service Access from User Experience, 2016-2020.

BetterNet aims at building and delivering a scientific and technical collaborative observatory to measure and improve the Internet service access as perceived by users. In this Inria Project Lab, we will propose new original user-centered measurement methods, which will associate social sciences to better understand Internet usage and the quality of services and networks. Our observatory can be defined as a vantage point, where: 1) tools, models and algorithms/heuristics will be provided to collect data, 2) acquired data will be analyzed, and shared appropriately with scientists, stakeholders and civil society, and 3) new value-added services will be proposed to end-users.

#### 8.2.5 Inria Exploratory Action "SNIDE"

We are leading of the Inria Exploratory Action SNIDE (Search Non neutratlIty DEtection) 2019-2023, involving Dionysos and MIMR (Grenoble). The involved researchers are Patrick Maillé and Bruno Tuffin.

Search engines play a key role to access content and are accused to bias their results to favor their own services among others. This has led to the sensitive search neutrality debate, similar to the network neutrality debate currently discussed on the role of ISPs. Our goal in this project is to develop and apply a methodology aiming at highlighting a bias and quantifying its impact.

An initial version of our meta-engine (which will be further develop by incorporating outlier detection tests) can be found at `https://snide.irisa.fr/`.

# 9 Dissemination

## 9.1 Promoting scientific activities

**Scientific events: organisation**

- Yann Busnel has been Local Chair of the *25th IEEE Symposium on Computers and Communications* (ISCC 2020), in Rennes, France, in July 2020 (finally online due to the pandemic situation).

- We planned to organize the mini-symposium entitled "Probabilistic approaches for studying blockchain dynamics" of the 8th European Congress of Mathematics, 5 - 11 July 2020, Portorozz, Slovenia, but it was cancelled due to pandemic reason.

**Member of the organizing committees**

- Yassine Hadjadj-Aoul was co-chair of the Steering Committee of the International Conference on Information and Communication Technologies for Disaster Management (ICT-DM), which is co-sponsored by IEEE. The next edition will be held at Hangzhou, China, in December 2021.

- Gerardo Rubino and Bruno Tuffin are members of the Steering Committee of the International Workshop on Rare Event Simulation (RESIM).

**Chair of conference program committees**

- Yassine Hadjadj-Aoul serves as a TPC co-chair of the 13th Wireless Days Conference (WD 2021), which is co-sponsored by IEEE, to be held virtually at Paris, in June 2021.

- Bruno Tuffin was TPC co-chair of the 17th International Conference on Economics of Grids, Clouds, Systems & Services (GECON), 15-17 September 2020 (virtual, initially Izola, Slovenia).

**Member of the conference program committees**

- Yassine Hadjadj-Aoul served as a TPC member for several international conferences including IEEE ICC, IEEE ISCC, IEEE Globecom, IEEE PIMRC, IEEE Mascots.

- Gerardo Rubino served as a TPC member for ICN 2020 (Lisbon, Portugal, Feb. 2020), eHealth 2020 (Thessaloniki, Grece, Oct. 2020) and IEEE Mascots 2020 (Nice, France, Nov. 2020).

- Bruno Tuffin served as a TPC member for MCQMC'20, IEEE 5G World Forum, ITC 32, IEEE GlobeCom 2020.

- Yann Busnel served as a TPC member for several international conferences including IEEE NCA 2020, IEEE ISCC 2020, AdHoc-Now 2020 and CoRes 2020;

#### 9.1.1 Journal

**Member of Editorial Boards**

- Yassine Hadjadj-Aoul was a guest editor of a special issue on: "Edge-Based AI for the Internet of Things", for the MDPI International Journal Sensors.

- Bruno Tuffin is Area Editor for *INFORMS Journal on Computing* and Associate Editor of *ACM Transactions on Modeling and Computer Simulation*.

- Bruno Sericola serves as associate editor for Performance Evaluation, since April 2015. He is also Editor in Chief of the books series "Stochastic Models in Computer Science and Telecommunications Networks", ISTE/WILEY, since March 2015.

- Gerardo Rubino is Associate Editor of the Journal of Dynamics & Games.

### 9.1.2 Invited talks

Yassine Hadjadj-Aoul made several invited and keynote talks or tutorials in 2020:

- *Evolutionary Actor-Multi-Critic Model for VNF-FG Embedding* [67]. Research Cluster - Network & Distributed Systems (GDR-RSD Days), Nantes, France.
- *Deep Reinforcement learning-based Network slicing* [68]. Bell Labs Spring Webinar, Virtual.
- *Access control in NB-IoT networks: a deep reinforcement learning strategy* [66]. GDR ARC "Session Automation and Communication Networks", Virtual.
- *5G enabled CAVs for Smart and Sustainable Mobility in Smart Cities* [65]. IEEE International Smart Cities Conference (ISC2) (ISC2'2020), Virtual.

Gerardo Rubino made several invited and keynote talks in 2020:

- Invited talk *Tight bounds of performance metrics computed on Markovian queuing models*, in the national Joint Mathematics Meeting of the AMS and the MAA, Denver, US, Jan. 2020.
- Keynote *Machine Learning Tools for Forecasting Correlated Time Series* in ICSADADS 2020 - International Conference on Statistical Applications in Data Analytics & Data Science, Coimbatore, India, Feb. 2020.

Yann Busnel made several invited and keynote talks in 2020:

- Keynote (virtual) *Attack-tolerant Sampling Methods over Sliding Window for Distributed Streams.* at International Conference on Data Sciences and Engineering, Cochin University, India, December 2020
- Invited Professor (virtual) *Blockchain Technology: Fundamentals of Synchronization and Distributed Consensus.* at VJTI Mumbai, India, August 2020
- Keynote *Sampling in blockchains.* at Finishing School / Workshop on Blockchain Technology, VJTI Mumbai, India, February 2020
- Invited seminar *The need for enlightened sampling and self-organisation in the supervision of large-scale networks.* at IISc Bangalore, India, February 2020

### 9.1.3 Leadership within the scientific community

- Yassine Hadjadj-Aoul is a member of the scientific committee of GT ARC (Automatique et Réseaux de Communication), since Nov. 2017
- Yassine Hadjadj-Aoul is a member of the "IEEE Sig on Big Data with Computational Intelligence" Special Interests Group under the IEEE COMSOC Big Data TC, Since June 2017
- Gerardo Rubino belongs to the CSV (the technical committee) of the Images and Networks Cluster of Brittany, France, since its foundation.
- Gerardo Rubino is the coordinator of the research action "Analytics and Machine Learning" between INRIA and Nokia Bell Labs.
- Yann Busnel is Co-Head of the MOOC Editorial Board at Institut Mines-Télécom, since 2018.
- Yann Busnel is Member of Member of Steering Committee at ResCom at GDR CNRS RSD, since 2017.
- Yann Busnel is Member appointed to the Improvement Council of the Master in Computer Sciences, University of Nantes, since 2017.

#### 9.1.4 Scientific expertise

- Yassine Hadjadj-Aoul was a remote assessor for the Irish Research Council (COALESCE Research Fund 2020)

#### 9.1.5 Research administration

- Bruno Sericola is responsible for the Inria Rennes-Bretagne Atlantique budget.
- Bruno Sericola is the leader of the research group MAPI (Math Appli Pour l'Info) the goal of which is to improve the collaboration between computer scientists and mathematicians.
- Bruno Sericola has been member of the research commission of the academic council of University of Rennes 1 until March 2020.
- Yann Busnel is *Head of* Network Systems, Cybersecurity and Digital Law *department* at IMT Atlantique, since 2017.
- *Head of* D2 – Network, Telecommunication and Services *department* at UMR IRISA, since 2019.

### 9.2 Teaching - Supervision - Juries

#### 9.2.1 Teaching

- Master: Bruno Tuffin, MEPS (probablility, queuing systems, simulation), 35 hours, M1, University of Rennes 1, France
- Master: Bruno Tuffin, GTA (Game Theory and Applications), 15 hours, M2, University of Rennes 1, France
- MOOC on Queuing Theory, available on EdX: Patrick Maillé (in charge of one week of class)
- MOOC on "Ose les métiers de l'industrie du futur", available on Fun: Yann Busnel (in charge of one week of class)
- IMT Atlantique 3rd year: Yann Busnel, Blockchain: Synchronisation and Token Economy, 3 hours.
- Licence: Bruno Sericola, Mathematics, 14h, L2, IUT/University of Rennes 1, France.
- Master: Bruno Sericola, Mathematics, 12h, M2, Istic/University of Rennes 1, France.
- Master: Bruno Sericola, Logistic and performance, 12h, M2, Faculté de sciences économiques, Univ of Rennes 1, France
- Master: Bruno Sericola, MEPS (performance evaluation), 36h, M1, Univ Rennes and ENS Rennes, France
- Master M1: César Viho, Networks:Rennes 1 from Services to protocols, 36 hours, Istic/University of Rennes 1, France
- Master M2: César Viho, Algorithms on graphs, 40 hours, Istic/University of Rennes 1, France
- Bachelor L2: César Viho, Network architecture and components, 16 hours, Istic/University of Rennes 1, France
- Master, 2nd year: Yassine Hadjadj-Aoul, Scalable Network Infrastructure (SNI), 10 hours, The Research in Computer Science (SIF) master and EIT Digital Master/University of Rennes 1, France
- Master, pro 2nd year: Yassine Hadjadj-Aoul, Multimedia streaming over IP (MMR), 48 hours, Esir/University of Rennes 1, France
- Master, pro 2nd year: Yassine Hadjadj-Aoul, Multimedia services in IP networks (RSM), 29 hours, Esir/University of Rennes 1, France

- Master, pro 2nd year: Yassine Hadjadj-Aoul, Software Defined Networks, 6 hours, Istic/University of Rennes 1, France
- Master, 2nd year: Yassine Hadjadj-Aoul, Video streaming over IP, 8 hours, Istic/University of Rennes 1, France
- Master: Yassine Hadjadj-Aoul, Introduction to networking (IR), 26 hours, Esir/University of Rennes 1, France
- Master: Yassine Hadjadj-Aoul, Mobile and wireless networking (RMOB), 20 hours, Esir/University of Rennes 1, France
- Master 2nd year: Yassine Hadjadj-Aoul, Overview of IoT technologies: focus on LPWAN, 2 hours, INSA, France
- Sofiene Jelassi is the manager of the master program "Heterogeneous Networks and Systems", Istic/University of Rennes 1, France
- Master pro 2nd year: Sofiene Jelassi, Supervision of heterogeneous networks, 32 hours, Istic/University of Rennes 1, France
- Master pro 2nd year: Sofiene Jelassi, Cloud & SDN virtualization, 32 hours, Istic/University of Rennes 1, France
- Master pro 2nd year: Sofiene Jelassi, Multimedia networks, 32 hours, Istic/University of Rennes 1, France
- Bachelor L1: Sofiene Jelassi, Programming Algorithms, 12 hours, SPM/University of Rennes 1, France
- Master, 2nd year: Gerardo Rubino, Scalable Network Infrastructure (SNI), 10 hours, The Research in Computer Science (SIF) master and EIT Digital Master/University of Rennes 1, France
- Supelec Rennes 3rd year: Gerardo Rubino, Dependability Analysis, 15 hours.
- Master 2nd year: Gerardo Rubino, Quality of Experience, twice 4 hours (two different groups of students), Esir/University of Rennes 1, France
- Master Pro 2nd year: Gerardo Rubino, Quality of Experience, 4 hours Esir/University of Rennes 1, France
- Esir/University of Rennes 1, 1st year, Gerardo Rubino, Graph theory and algorithms, 24 hours, France
- Esir/University of Rennes 1, 2nd year, Gerardo Rubino, Introduction to graph algorithmes in routing, 8 hours, France

#### 9.2.2 Supervision

- PhD in progress: Ahcene Boumhand, "Apprentissage Multitâche pour la Découverte de Contextes du Home "; Started in October 2020. CIFRE Thesis with Orange Labs/University of Rennes 1, Advisors: César Viho (Université Rennes 1) and Yassine Hadjadj-Aoul (Université Rennes 1) and Kamal Deep-Singh (UJM Saint-Etienne).
- PhD in progress: Sid Ali Hamideche, "Automation for beyond 5G Mobile Networks"; Started in July 2020. CIFRE Thesis with Université Rennes 1 and Orange labs, Advisors: César Viho (Université Rennes 1) and Kamal Deep-Singh (UJM Saint-Etienne).
- PhD in progress: Ximun Castoreo, "Measurements to check network neutrality", University of Rennes 1, Started 10/2018, supervised by Bruno Tuffin.

- PhD in progress: Ayman Chouayakh, “Auctions for spectrum allocations in 5G”, CIFRE Thesis with Orange Labs/University of Rennes 1, Started 03/2017, supervised by Patrick Maillé.
- PhD in progress: Leo Lavaur, “Outils de Threat Intelligence pour l’indexation des menaces de l’IdO et le partage coopératif”, IMT Atlantique. Started on Oct. 2020. Advisors: F. Autrel (IMT Atlantique), Y. Busnel (IMT Atlantique), M.-O. Pahl (IMT Atlantique).
- PhD in progress: Jérôme Henry, “Indoor localization using the most recent standards of 802.11”, IMT Atlantique. Started on Oct. 2019. Advisors: N. Montavont (IMT Atlantique), Romaric Ludinard (IMT Atlantique), Y. Busnel (IMT Atlantique).
- PhD in progress: Anouar Rkhami, “Data analytics for optimized resources’ management in future 5G networks”; started on Oct. 2018; Advisors: Gerardo Rubino and Yassine Hadjadj-Aoul, and Abdelkader Outtagarts, Inria – Nokia Bell labs.
- PhD in progress: Imane Taibi, “Big data analysis for network monitoring and troubleshooting”; started on Nov. 2017; Advisors: Gerardo Rubino, Chadi Barakat and Yassine Hadjadj-Aoul, Inria.
- PhD in progress: Ali Hodroj, Enhancing content delivery to multi-homed users in broadband mobile networks, started in November 2015; supervisors: Bruno Sericola, Marc Ibrahim and Yassine Hadjadj-Aoul, University Rennes 1 and St Joseph University of Beyrouth.
- PhD in progress: Mohamed Rahali, “Machine learning-based monitoring and management for hybride SDN networks”; started on Oct. 2017; Advisors: Gerardo Rubino, INRIA, and Jean-Michel Sanner, B-COM.
- Post-doc in progress: Frédérique Robin, Modelling the dynamic behaviour of blockchains and analyzing their performance, Inria Rennes. Supervisors: Bruno Sericola and Emmanuelle Anceaume from team Cidre, until September 2020.

**Thesis defended in 2020:**

- PhD: Jean-Michel Sanner; Cifre Grant, Orange Labs, “SDN technologies for network services performances adaptation of carriers networks”, Defense in July 2019. Supervisors: Yassine Hadjadj-Aoul and Gerardo Rubino.
- PhD: Hamza Ben Ammar, “Network and cache resources optimization for efficient media content delivery in CCN”, Defense in March 2019; advisors: Yassine Hadjadj-Aoul, Gerardo Rubino and Soraya Ait Chellouche, University Rennes 1 XXcitebenammar:tel-02109693.
- PhD: Illyyne Saffar, “Machine Learning to Infer User Behavior in 5G Autonomic Networks”; Defense in November 2020. Advisors: César Viho (Université Rennes 1) and Kamal Deep-Singh (UJM Saint-Etienne) and Marie Line Alberi-Morel (Nokia Bell labs), Université Rennes 1 and Nokia Bell labs.

#### 9.2.3 Juries

- Bruno Sericola was member of the selecting board for the recruitment of Inria researchers in 2020.
- Yann Busnel was member of the selecting board for the recruitment of MCF at INSA Lyon in 2020.
- Yann Busnel has been Reviewer for the PhD defense of Chandan Gautam (IIT Indore), on 08/01/2020.
- Yann Busnel has been Examiner for the PhD defense of Routa Moussaieb (IMT Atlantique), on 07/10/2020.

### 9.3 Popularization

#### 9.3.1 Internal or external Inria responsibilities

- Yann Busnel is a member of Development Council of Computer Sciences Master at Université de Nantes (2017–*).

#### 9.3.2 Interventions

- G. Rubino makes regular presentations to high school students about the research work in general, and specific technical topics in particular. Current talks:
  - Randomness as a tool
  - Internet as a research problem
  - Great challenges in maths: the Riemann Hypothesis
  - Great challenges in math/computer science: the "P versus NP" problem

# 10 Scientific production

## 10.1 Major publications


[1] E. Anceaume and Y. Busnel. 'A Distributed Information Divergence Estimation over Data Streams'. In: *IEEE Transactions on Parallel and Distributed Systems* 25.2 (Feb. 2014), pp. 478–487. DOI: 10.1109/TPDS.2013.101. URL: https://hal.archives-ouvertes.fr/hal-00998708.

[2] Y. Hadjadj-Aoul and T. Taleb. 'An adaptive fuzzy-based CAC scheme for uplink and downlink congestion control in converged IP and DVB-S2 networks'. In: *IEEE Transactions on Wireless Communications* 8.2 (Feb. 2009), pp. 816–825.

[3] Y. Hayel, D. Ros and B. Tuffin. 'Less-than-Best-Effort Services: Pricing and Scheduling'. In: *23rd IEEE Infocom Conference*. Hong-Kong, China, Mar. 2004.

[4] S. Jelassi and G. Rubino. 'A perception-oriented Markov model of loss incidents observed over VoIP networks'. In: *Computer Communications* 128 (Sept. 2018), pp. 80–94. DOI: 10.1016/j.comcom.2018.06.009. URL: https://hal.inria.fr/hal-01962917.

[5] P. Leguesdron, J. Pellaumail, G. Rubino and B. Sericola. 'Transient analysis of the M/M/1 queue'. In: *Advances in Applied Probability* 25.3 (Sept. 1993), pp. 702–713.

[6] P. Maillé and B. Tuffin. *Telecommunication Network Economics: From Theory to Applications*. Cambridge University Press, 2014, p. 288. URL: https://hal.inria.fr/hal-00908598.

[7] S. Mohamed and G. Rubino. 'A study of real-time packet video quality using random neural networks'. In: *IEEE Trans. Circuits Syst. Video Techn.* 12.12 (2002), pp. 1071–1083. DOI: 10.1109/TCSVT.2002.806808. URL: https://doi.org/10.1109/TCSVT.2002.806808.

[8] H. Nabli and B. Sericola. 'Performability analysis: a new algorithm'. In: *IEEE Transactions on Computers* 45.4 (1996), pp. 491–494.

[9] B. Oreshkin, N. Régnard and P. L'Ecuyer. 'Rate-Based Daily Arrival Process Models with Application to Call Centers'. In: *Operations Research* 64.2 (2016). URL: https://hal.inria.fr/hal-01399539.

[10] G. Rubino and B. Sericola. 'A finite characterization of weak lumpable Markov processes. Part II: The continuous time case'. In: *Stochastic Processes and their Applications* 45 (1993), pp. 115–126.

[11] G. Rubino and B. Tuffin, eds. *Rare Event Simulation using Monte Carlo Methods*. John Wiley & Sons, 2009.

[12] A. Samba, Y. Busnel, A. Blanc, P. Dooze and G. Simon. 'Predicting file downloading time in cellular network: Large-Scale analysis of machine learning approaches'. In: *Computer Networks* 145 (Nov. 2018), pp. 243–254. DOI: 10.1016/j.comnet.2018.09.002. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-01951758.

[13] B. Tuffin. 'Bounded Normal Approximation in Highly Reliable Markovian Systems'. In: *Journal of Applied Probability* 36.4 (1999).

## 10.2 Publications of the year

### International journals

[14] H. Ben-Ammar and Y. Hadjadj-Aoul. 'A GRASP-based Approach for Dynamic Cache Resources Placement in Future Networks'. In: *Journal of Network and Systems Management* 28.3 (July 2020), pp. 457–477. DOI: 10.1007/s10922-020-09521-4. URL: https://hal.inria.fr/hal-03122222.

[15] Y. Busnel. 'Panorama des modèles de flux de données à large échelle'. In: *Revue des Sciences et Technologies de l'Information - Série TSI : Technique et Science Informatiques* (2020). DOI: 10.3166/TSI..1-27. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-03034373.

[16] Y. Hadjadj-Aoul and S. Aït-Chellouche. 'Access Control in NB-IoT Networks: A Deep Reinforcement Learning Strategy'. In: *Information* 11.11 (Nov. 2020), p. 541. DOI: 10.3390/info11110541. URL: https://hal.inria.fr/hal-03122210.

[17] N. Jara, H. Pempelfort, G. Rubino and R. Vallejos. 'A fault-tolerance solution to any set of failure scenarios on Dynamic WDM Networks with wavelength continuity constraints'. In: *IEEE Access* 8 (20th Jan. 2020), pp. 21291–21301. DOI: 10.1109/ACCESS.2020.2967751. URL: https://hal.inria.fr/hal-03122447.

[18] N. Jara, H. Pempelfort, G. Rubino and R. Vallejos. 'How much the wavelength dimensioning methods and a tightened QoS provision impact on the dynamic WDM optical networks capacity? (NESIM Best Research Award)'. In: *Optical Switching and Networking* 35 (Jan. 2020), pp. 1–12. DOI: 10.1016/j.osn.2019.100540. URL: https://hal.inria.fr/hal-02431514.

[19] A. Kumar, K. Abhishek, M. Ghalib, P. Nerurkar, K. Shah, M. Chandane, S. Bhirud, D. Patel and Y. Busnel. 'Towards cough sound analysis using the Internet of things and deep learning for pulmonary disease prediction'. In: *Transactions on emerging telecommunications technologies* (2020). DOI: 10.1002/ett.4184. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-03035289.

[20] A. Kumar, K. Abhishek, A. Kumar Singh, P. Nerurkar, M. Chandane, S. Bhirud, D. Patel and Y. Busnel. 'Multilabel classification of remote sensed satellite imagery'. In: *Transactions on emerging telecommunications technologies* (May 2020), e3988. DOI: 10.1002/ett.3988. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-02749819.

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[22] P. Nerurkar, S. Bhirud, D. Patel, R. Ludinard, Y. Busnel and S. Kumari. 'Supervised Learning model for Identifying illegal activities in Bitcoin'. In: *Applied Intelligence* (2020). DOI: 10.1007/s10489-020-02048-w. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-03028829.

[23] P. Nerurkar, D. Patel, Y. Busnel, R. Ludinard, S. Kumari and M. Khurram Khan. 'Dissecting bitcoin blockchain: Empirical Analysis of Bitcoin network (2009-2020)'. In: *Journal of Network and Computer Applications* (11th Dec. 2020). DOI: 10.1016/j.jnca.2020.102940. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-03030340.

[24] N. Torres-Cruz, M. Rivero-Angeles, G. Rubino, R. Menchaca-Mendez, R. Menchaca-Mendez and D. Ramirez. 'A comprehensive analytical framework for VoD services in hybrid CDN-P2P systems'. In: *Journal of Network and Computer Applications* 161 (Apr. 2020), p. 17. DOI: 10.1016/j.jnca.2020.102643. URL: https://hal.inria.fr/hal-03122777.

### International peer-reviewed conferences

[25] P. T. Anh Quang, Y. Hadjadj-Aoul and A. Outtagarts. 'On Using Deep Reinforcement Learning for VNF Forwarding Graphs Placement'. In: NoF 2020 - 11th International Conference on Network of the Future. Bordeaux, France, 12th Oct. 2020, pp. 126–128. DOI: 10.1109/NoF50125.2020.9249090. URL: https://hal.inria.fr/hal-03130842.

[26] Y. Busnel, C. Caillouet and D. Coudert. 'VESPA, ou l'art de coordonner une flotte de drone sans leader'. In: ALGOTEL 2020 – 22èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications. Lyon, France, 28th Sept. 2020, pp. 1–4. URL: https://hal.inria.fr/hal-02796530.

[27] Y. Busnel and Y. Tillé. 'Attack-tolerant Unequal Probability Sampling Methods over Sliding Window for Distributed Streams'. In: ICCDA 2020 : 4th International Conference on Compute and Data Analysis. Proceedings of the 2020 the 4th International Conference on Compute and Data. San Jose, United States: https://dl.acm.org/conference/iccda, 9th Mar. 2020, pp. 72–78. DOI: 10.1145/3388142.3388162. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-02456880.

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[30] P. W. Glynn, M. K. Nakayama and B. Tuffin. 'Comparing Regenerative-Simulation-Based Estimators of the Distribution of the Hitting Time to a Rarely Visited Set'. In: Winter Simulation Conference 2020. Orlando, United States, 13th Dec. 2020. URL: https://hal.inria.fr/hal-02554131.

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[32] A. Hodroj, M. Ibrahim and Y. Hadjadj-Aoul. 'Parallel Streaming for a Multi-homed Dash client'. In: IWCMC 2020 - International Wireless Communications and Mobile Computing. Limassol / Virtual, Cyprus, 15th June 2020, pp. 63–68. DOI: 10.1109/IWCMC48107.2020.9148354. URL: https://hal.inria.fr/hal-03122242.

[33] A. Kieffer, P. Maillé and B. Tuffin. 'Non Neutrality With Users Deciding Differentiation: A Satisfying Option?' In: IEEE/ACM International Symposium on Modelling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS) Workshop. Nice, France, 2020. URL: https://hal.inria.fr/hal-02566587.

[34] P. Maillé and B. Tuffin. 'A Network Reliability Game'. In: 17th International Conference on the Economics of Grids, Clouds, Systems, and Services (GECON), Izola, Slovenia, 2020. URL: https://hal.inria.fr/hal-01938939.

[35] M. K. Nakayama, Z. T. Kaplan, B. Tuffin and P. L'Ecuyer. 'Quantile Estimation Via a Combination of Conditional Monte Carlo and Randomized Quasi-Monte Carlo'. In: Winter Simulation Conference 2020. Orlando, United States, 13th Dec. 2020. URL: https://hal.inria.fr/hal-02551516.

[36] P. Nerurkar, Y. Busnel, R. Ludinard, K. Shah, S. Bhirud and D. Patel. 'Detecting Illicit Entities in Bitcoin using Supervised Learning of Ensemble Decision Trees'. In: ICICM 2020 : 10th International Conference on Information Communication and Management. Paris, France, Aug. 2020, pp. 25–30. DOI: 10.1145/3418981.3418984. URL: https://hal-imt-atlantique.archives-ouvertes.fr/hal-02952081.

[37] Q. T. A. Pham, Y. Hadjadj-Aoul and A. Outtagarts. 'Evolutionary Actor-Multi-Critic Model for VNF-FG Embedding'. In: CCNC 2020 - IEEE Consumer Communications & Networking Conference. Las Vegas, United States, 10th Jan. 2020, pp. 1–6. URL: https://hal.inria.fr/hal-02428006.

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