INRIA, EVALUATION OF THEME Networks and Telecommunications

PROJECT-TEAM RAP

Project-team title: RAP.

Scientific leader: Philippe Robert.

Research center: Paris — Rocquencourt.

1. Personnel

Personnel (October 2007).

	Misc.	INRIA	CNRS	University	**Total**
DR (1) / Professors		1			**1**
CR (2) / Assistant Professors		1			**2**
PhD Students		2			**2**
Total		**4**			**4**
External Collaborators	1 (Orange Labs)			1	**2**

Personnel (March 2012).

	Misc.	INRIA	CNRS	University	**Total**
DR (1) / Professors		2			
CR (2) / Assistant Professors		1			
Permanent Engineer					
Temporary Engineer					
PhD Students	1 (INRA)	2			
Post-Doc.					
Total	**1**	**5**			**6**
External Collaborators	1 (Orange Labs)			2	
Visitors	1 (1 year)				

Changes in staff.

DR / Professors CR / Assistant Professors	Misc.	INRIA	CNRS	University	total
Arrival		1		1	

Current composition of the project-team :

— Virginie Collette, Assistant
— Mathieu Feuillet, INRIA PhD Student, École Polytechnique, corps des Mines
— Christine Fricker, INRIA Researcher
— Emanuele Leoncini, INRA PhD Student, École Polytechnique
— Philippe Robert, INRIA Research Director
— James Roberts, INRIA Research Director
— Nada Sbihi, INRIA PhD Student, University Pierre et Marie Curie

External Collaborators.

— Fabrice Guillemin, Orange Labs
— Hanène Mohamed, Associate Professor University Paris Ouest Nanterre La Défense
— Danielle Tibi, Associate Professor Paris Denis Diderot

Date: March 2012.

Current position of former project-team members.

— Yousra Chabchoub, PhD now Associate Professor at Engineering School ISEP
— Hanène Mohamed, Associate Professor University Paris Ouest Nanterre La Défense
— Florian Simatos, PhD now Post-Doc at the University of Eindhoven

Last INRIA enlistments.

— James Roberts, Research Director since 2009.

Other comments:

— Philippe Robert has an Associate Professor Position at the Ecole Polytechnique

2. Work progress

Keywords. Optical Network. Content Networks. Stochastic Models — Performance Evaluation. Scaling techniques for Markov Processes.

Context and overall goal of the project. RAP project-team has been created in 2004 to formalize and extend a close collaboration with Fabrice Guillemin and his collaborators at France Telecom R&D (now Orange Labs) at Lannion. Acronym RAP stands, in French, for "Communication Networks, Algorithms and Probability". The respective strengths of the two teams are an expertise of modeling issues of communication networks and their operational aspects for the France Telecom team and, for the INRIA team, an experience in probabilistic methods and in mathematical modeling of communication networks.

As a general philosophy, stochastic networks are seen as an application domain of probabilistic methods rather than a restricted research domain with ad-hoc basic results. In this perspective, close contacts with the Laboratory of Probability of the University Pierre et Marie Curie and Paris Denis Diderot and CMAP laboratory of École Polytechnique have been established for some time now. We believe that new stochastic models motivated by the emerging architectures of networks should initiate the development of originals methods in probability theory. In this domain the team RAP develops scaling methods to investigate the behavior and performances of algorithms and architectures of communication networks.

The second important point is the design of algorithms for communication networks. During the evaluation period, we designed algorithms for estimating IP traffic and detecting DOS attacks, for allocating bandwidth in optical networks and investigated the new ICN architectures (Information Centric Networks). As much as possible, these studies rely on significant data sets.

Objectives for the evaluation period. From the evaluation document of 2007 in the section on future work, we wrote "Our collaboration with France Telecom will be devoted to two subjects, one on security where some work has already started and another one which is more prospective on resource allocation problems in optical networks", we studied during this evaluation period:

(1) Sampling and Security Issues.
(2) Resource Allocation Algorithms in optical networks.
(3) Equilibrium and Dynamics of Large Stochastic Networks.

A new activity on a prospective network architecture has recently started (2011):

(1) CCN, (Content Centric Networks).

2.1. **Objective 1: Sampling and Security Issues.**

Personnel.

— Yousra Chabchoub, INRIA PhD
— Christine Fricker INRIA Researcher
— Hanène Mohamed, Associate Professor University Paris Ouest Nanterre La Défense
— Philippe Robert INRIA Research Director
— Danielle Tibi Associate Professor Paris Denis Diderot

Project-team positioning. This research topic started in 2004, we describe only the last results obtained in this domain. The general goal of the research in this domain was of designing *on line* algorithms to analyze and control the IP traffic of commercial networks. The close collaboration with France Telecom is of special value here since we had an access to the *ADSL traces* (commercial traffic) which is a significant advantage to assess the impact of algorithms on real traffic.

Scientific achievements. For this topic we have investigated the problem of designing an on-line algorithm for identifying long flows (also called sometimes *elephants*) in IP traffic. From the point of view of traffic engineering, this is an important issue. This is also an illustrative and simple example exhibiting the importance of the fact that on-line algorithms *have to adapt to traffic variations*. Variations within a flow of packets are frequent, this leads to a complex stochastic behavior in the arrival patterns of packets. This is an aspect which is sometimes underestimated in the technical literature. Additionally, as it will be seen below, the methods developed for this problem can be in fact used to design a quite efficient anomaly detection algorithm.

An algorithm which can satisfactorily run in some instances on limited traces can fail when handling a large traffic trace (e.g., several hours of transit network IP traffic) because of various reasons :

(1) Performances deteriorate with time. The size of data structures increases without bounds as well as the time taken by the algorithm to update them.
(2) Poor performances occur even from the beginning. Quite often, algorithms depend (sometimes in a hidden way in the technical literature) on constants directly related to the traffic intensity. For a limited set of traces, they can be tuned "by hand" to get reasonable performances. This procedure is, however, not acceptable in the context of an operational network. As a general requirement, it is highly desirable that the constants used by algorithms automatically adapt, as simply as possible, to varying traffic conditions.

A probabilistic algorithm to count, with a minimal memory buffer, long flows (elephants) in Internet traffic has been designed to get their characteristics such as IP addresses and sizes. The algorithm must be adapted to very different traffic characteristics and also to traffic variations. The algorithm is based on Bloom filters: for each packet, the IP address is sent via independent hashing functions to filters. The idea is that, if the cases of the filters have counters, while each packet of one flow is hashed to the same cases, the long flows (more than 20 packets) could be approximately counted. For that, the filters must be cleared for time to time, in order to avoid accumulation of short flows, very numerous, which pollute the filters. Contrary to the algorithms of the literature where filters are cleared periodically more or less independently of the traffic. We designed an algorithm which uses an adaptive refreshment mechanism of the cache based on the filling rate of the filter. In practice, the algorithm has been tested successfully on a wide set of real traces: commercial Orange traces and academic traces.

Attack Detection. An interesting application field of these methods is the detection of anomalous behavior, for instance due to denial of service. During such an attack, a victim is the target of a huge number of small flows coming from numerous sources. An on-line identification of such anomalous behavior is necessary for a network administrator to be able to react quickly and to limit the impact of the attack on the victim. The main problem is in this case to be able to separate quantitatively "normal" variations of traffic from these sudden bursts of traffic. Here again, adaptive properties of the detection algorithms to traffic conditions are essential to distinguish between normal variations of traffic and attacks. We have mainly investigated SYN flooding and volume flooding which are the most common DoS (Denial of Service) attacks. Using a convenient definition of a flow, these attacks can be considered as long flows. However, in the context of attack detection, the refreshing mechanism of the multistage filter has a different purpose. It should eliminate quickly all normal flows, for this reason a more aggressive refreshing method has to be used. Moreover attacks are always defined as a notable deviation from a standard behavior. To describe the standard traffic, the main idea of the algorithm is to evaluate a

varying average, denoted by m, of the largest flow in several sliding time windows. The quantity m is periodically actualized in order to adapt to varying traffic conditions. It is a weighted average that takes into account all its past values to follow carefully traffic variations. A flow is considered as an attack if it deviates significantly from the actual varying average.

The algorithm was tested against several traces from France Telecom IP backbone network. The alarms detected by the algorithm coincide very often with anomalous behaviors. A distributed version of the algorithm at the level of a network has been proposed.

Analytical Study of the Algorithm to Count Long Flows. The model has been simplified in order to evaluate the impact of refreshment on the accuracy of the estimation of the number of long flows. See Chabchoub et al [6] below. This model is related to the so-called power of choices in Bloom filters or in queues which has attracted much attention recently. Limit theorems of the empirical distribution of the filter have been obtained when the filter size m is large. The limit is deterministic and has a nice interpretation in terms of queues. The main conclusion of the analysis is that the threshold r for refreshment must not reach some critical value, otherwise the proportion of false positives (short flows considered as long flows) is very high. Nevertheless, the threshold r must remain high enough in order not to miss long flows.

Main Publications

[1] Yousra Chabchoub. *Analyse et modélisation du trafic Internet*. PhD thesis, Université Pierre et Marie Curie, October 2009. PDF

[2] Yousra Chabchoub, Christine Fricker, Fabrice Guillemin, and Philippe Robert. On the statistical characterization of flows in Internet traffic with application to sampling. *Computer Communications*, 33(1):103–112, 2010. PDF.

[3] Christine Fricker, Fabrice Guillemin, and Philippe Robert. An identification problem in an urn and ball model with heavy tailed distributions. *Probability in the Engineering and Informational Sciences*, 24(1):77—97, 2010. PDF.

[4] Yousra Chabchoub, Christine Fricker, and Hanène Mohamed. Analysis of a bloom filter algorithm via the supermarket model. In *Proceedings of ITC21*, September 2009. PDF.

[5] Yousra Chabchoub, Christine Fricker, Fabrice Guillemin, and Philippe Robert. Inference of flow statistics via packet sampling in the Internet. *IEEE Communications Letters*, 12(12):897 — 899, 2008. PDF.

[6] Yousra Chabchoub, Christine Fricker, Frédéric Meunier, and Danielle Tibi. Analysis of an algorithm catching elephants on the Internet. In *Fifth Colloquium on Mathematics and Computer Science*, DMTCS Proceedings Series, pages 299–314, September 2008. PDF.

Collaborations. We had several co-authors from other research centers:

Fabrice Guillemin, Orange Labs
Frédéric Meunier, ENPC

Additionally fruitful contacts with Philippe Flajolet of the INRIA team ALGORITHMS and his PhD students have been established on a probabilistic counting algorithm. Its application to IP traffic has been the subject of an internship.

Interestingly, a part of the research of the team on sampling issues of the Internet traffic has also been investigated by INRIA research TEAM RESO, in Patrick Loiseau PhD thesis in particular where our algorithm is discussed. Philippe Robert was one of the reviewers of this PhD thesis.

External support.

- RNRT project "OSCAR" on the attack detection in the Internet. Two years contract starting from April 2006. Participants: ENS Lyon, Get, INRIA, France Telecom, Laas, LIP6.
- CRE Contract "Mathematics and Algorithms for Internet Measurements" with Orange Labs.

Self assessment. This research topic is now finished for our research team.

Concerning the problem of sampling, i.e. the information on the traffic available when 1/(500,1000) of the IP packets are sampled, a statistical model of the traffic has to be done. In our view, the mathematical modeling of the size (nb of packets or size in bytes) of IP flows is a key and somewhat underestimated problem. Our contribution has been of showing that a "universal model" of the distribution of packets sizes cannot be a *robust* model. Instead, if statistics are done on a convenient limited time interval, a model can be valid and, more important, its parameters estimated in a *robust way*.

Traffic parameters vs Universal parameters. Some of the algorithms in the literature seem to neglect the determination of some of the parameters of the algorithm depending on traffic characteristics. We took a great care in this domain for the algorithms we designed for traffic estimation and attack detection. A "fine tuning" of these parameters for each traffic trace cannot be an acceptable solution.

2.2. **Objective 2: Dynamic Bandwidth Allocation in Optical Networks.**

Personnel.

— Nelson Antunes, Visiting Scientist, University of Algarve
— Christine Fricker INRIA Researcher
— Philippe Robert INRIA Research Director
— James Roberts INRIA Research Director

Project-team positioning. The development of dynamic optical switching is widely recognized as an essential requirement to meet anticipated growth in Internet traffic. Since September 2009, in collaboration with Orange Labs RAP has begun an investigation into the traffic management and performance evaluation issues that are particular to this technology.

We investigated the problem of bandwidth allocation in these networks. It consists of establishing, in a dynamical environment, light paths between nodes of the network. These studies differ from static allocation of light paths problem analyzed in the late 1990's, by the INRIA team MASCOTTE for example. The highly dynamic traffic of the Internet has a strong impact on the set of possible algorithms. Another important point is that to take advantage of the high throughputs of this technology, data cannot be stored at intermediate nodes within the network as it is the case in the Internet now.

The choice of algorithms for optical networks strongly depends on the technological framework assumptions. This is always the case for communication networks in general (like wireless networks for example), but this is perhaps more sensitive in the case of optical networks: how many wavelengths ? Is it possible to use different wavelengths on the same light path ? How many transmitters/receivers at a given node ? one per wavelength or does one use tunable transmitters/receivers ? Does one use delay lines ? Some of the components do not exist now but MAY be available in a near future, or some of them may have a prohibitive cost, ... The technological context has clearly a *high* impact on bandwidth allocation for these networks. For this reason, the literature may appear somewhat confusing to the newcomer.

Our approach has been of considering in general only a minimalistic framework: one wavelength per light path, no electronic conversion, and routing is done in a passive way through appropriate components which deflect transmissions according to their wavelengths.

Scientific achievements.

PON in the access. We first considered the case of Passive Optical Networks (PON) in the access. Users are connected to the Internet via Optical Network Units (ONUs) which manage packet queues for one or several domestic or business users. The ONUs are controlled from an optical line termination (OLT) equipment that realizes the interface with the electronic packet switched network and manages downstream and upstream traffic. Passive splitters are used to broadcast downstream optical signals to the ONUs and to merge upstream signals destined to the OLT. We have analyzed a future version of the PON where multiple channels are created over the same fibre network using Wavelength Division Multiplexing (WDM).

Each ONU receives all downstream traffic on the wavelengths to which it has access and extracts its own packets based on the destination address. For upstream traffic, the ONUs must coordinate their upstream transmissions to the OLT in order to avoid collisions at the splitter (and OLT). A significant contribution has been to design an original Dynamic Bandwidth Allocation (DBA) algorithm for WDM PONs and to evaluate its performance. Figure 1 illustrates the main components of the Ethernet PON (EPON).

In reference Antunes et al. [5] below, a novel DBA algorithm used to manage the upstream resource in a WDM EPON has been proposed. It implements a protocol that guarantees full utilization of the channels while ensuring access is fair to all users, even when the propagation time can be large in future long reach PONs. The DBA emulates a multi-server polling system and has considerably better performance characteristics than previously proposed algorithms in terms of both capacity and delay.

The performance of this DBA has also been investigated under the assumption that users access the fibre via optical network units equipped with tunable transmitters. This implies users can use any of the multiple wavelengths to transmit their data but only within the limit determined by the number of transmitters they possess. The underlying service model is a multi-server polling system with both server limits and gate limits. This system is known to be intractable. In Antunes et al. [6] and Robert

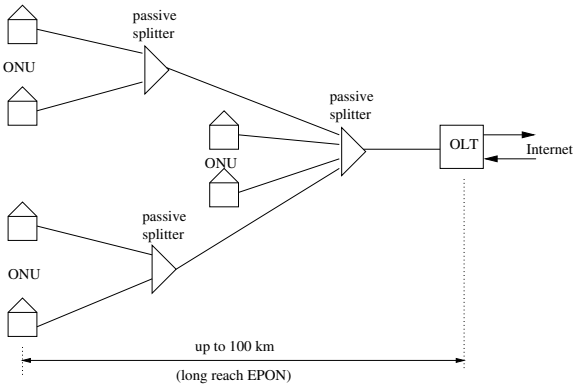

FIGURE 1. EPON components: ONUs, passive splitters and OLT

and Roberts [4] below we derived large system asymptotic, mean-field approximations that yield accurate closed-form solutions. See the section on large stochastic networks.

Extensions to meshed networks. Our experience with the access network has subsequently been applied, first to design an original passive optical metropolitan area network and, second to propose a novel multi-point-to-multi-point light-path structure that can be used to build the wide area network of a typical national Internet domain.

The time-domain wavelength interleaved networking (TWIN) concept defined by Saniee and co-workers at Alcatel-Lucent Bell Labs allows the construction of metropolitan area networks using passive optical components: tunable transmitters, wavelength selective optical cross connects and burst mode receivers. In Robert and Roberts [3] below, we have proposed an original MAC protocol for this network that is largely inspired by the above described DBA algorithm for the EPON. Unlike the EPON DBA, however, management of source-destination traffic streams in this proposal is flow-aware with the size of allocated time slices being proportional to the number of active flows. This allocation algorithm emulates a network-wide, distributed fair queuing scheduler, bringing the well-known implicit service differentiation and robustness advantages of this mechanism to the metro area network. We have demonstrated by mathematical models and simulation that the proposed network architecture has excellent performance.

It is difficult to apply TWIN in a wide area network due both to scalability issues (each destination must have a unique wavelength) and to the fact that packet latency becomes too big when nodes are far apart. To overcome these difficulties, we have invented a novel multi-point-to-multi-point light path structure together with a mechanism for sharing its bandwidth that can be used to build a passive optical mesh network in replacement of the current electronic core. This invention has been patented jointly with Orange. See reference Indre et al. [46] page 20.

Mathematical Models. Due to high throughputs of these networks, simulations show that, as long as the network can accommodate the incoming flows, the delays experienced by connections are small. The main issue for these networks is therefore of determining the capacity region of these systems. The models investigated in our work are related to the well known *polling systems*, where servers are wavelengths with some constraints on the location of servers which depend on the architecture of the network. It turns out that this is, in general, a difficult problem. A *mean field limit* technique has been used to estimate the capacity of a limited-gated multi-server polling system with a limit on the number of servers a given station can use simultaneously. The approximation provides an expression for the stability limit under very general assumptions about the traffic process and system configuration.

MAIN PUBLICATIONS

[1] Davide Cuda, Raluca-Maria Indre, Esther Le Rouzic, and James Roberts. Getting routers out of the core: Building an optical wide area network with "multipaths". submitted, 2011. PDF

[2] Nelson Antunes, Christine Fricker, and James Roberts. Stability of multi-server polling system with server limits. *Queueing Systems, Theory and Applications*, 68(3-4):229–235, 2011. PDF.

[3] Philippe Robert and James Roberts. A flow-aware MAC protocol for a passive optical metropolitan area network. In *23th ITC Specialist Seminar on Internet Traffic Engineering and Traffic Management*, San Francisco, 2011. PDF.

[4] Philippe Robert and James Roberts. A mean field approximation for the capacity of server-limited, gate-limited multi-server polling systems. *SIGMETRICS Performance Evaluation Review*, 38(2):24–26, 2010. PDF.

[5] Nelson Antunes, Christine Fricker, Philippe Robert, and James Roberts. Gate-driven dynamic bandwidth allocation for WDM epon. In *GLOBECOM 2010*, Miami, 2010. IEEE Communications Society. PDF.

[6] Nelson Antunes, Christine Fricker, Philippe Robert, and James Roberts. Traffic capacity of large WDM passive optical networks. In *22th ITC Specialist Seminar on Internet Traffic Engineering and Traffic Management*, pages 333–344, Amsterdam, September 2010. IEEE Communications Society. PDF.

Collaborations. Our activity on optical networking is carried out in collaboration with Orange Labs (Esther Le Rouzic and Raluca Indre). We have also established contacts with Alcatel-Lucent Bell Labs and had fruitful exchanges with Iraj Saniee and his team on their proposed time-domain wavelength interleaved networking architecture (TWIN).

External support. We had two research contracts with Orange Labs on this topic.

— CRE contract "Algorithmes d'allocation de ressources dans les réseaux optiques" with Orange Labs on bandwidth allocation algorithm in optical networks. Two years starting from 2009.

— CRE with Orange Labs " Dynamical Optical Networking in the Internet". Contract on bandwidth allocation algorithm in optical networks. Duration 2 years starting from 01/01/12.

Self assessment. We designed original bandwidth allocation algorithms for optical network. In our view, the strengths of these algorithms are the following

— They assume a minimal technological environment and therefore can be deployed. This is an important aspect, especially in this context. One of the goals of the European project proposal CELTICS-PLUS SASER which has been recently submitted is of having a platform of experimentation of algorithms for optical networks.

— In the case of PON networks, their performances in terms of capacity are superior to the existing algorithms of the literature.

— The extension we have done of the ideas used for PON networks to a wide area network is really promising. Not only, this would provide higher throughputs for these networks, but it would also simplify the architecture of the network by removing an important fraction of internal routers.

2.3. **Objective 3: Content Centric Networks (CCN).**

Personnel.

— Christine Fricker INRIA Researcher
— Philippe Robert INRIA Research Director
— James Roberts INRIA Research Director
— Nada Sbihi INRIA PhD Student, University Pierre et Marie Curie

Project-team positioning. CCN is a new paradigm for the future Internet: rather than interconnecting remote hosts like IP, the network directly manages the information objects that users publish, retrieve and exchange. CCN has been proposed by Van Jacobson and colleagues at the Palo Alto Research Center (PARC). In CCN, content is divided into packet-size chunks identified by a unique name with a particular hierarchical structure. Packets in CCN are of two types: Interests and Data. Each Data packet carries a payload of several kilobytes, preceded by a header consisting of a unique name followed by signatures and other authentication data. A Data packet is returned in response to an Interest packet bearing the same name. The name and content can thus be cryptographically encoded and signed, providing a range of security levels. Packets in CCN carry names rather than addresses and this has a fundamental impact on the way the network works. Security concerns are addressed at the content level, relaxing requirements on hosts and the network. Users no longer need a universally known address, greatly facilitating management of mobility and intermittent connectivity. Content is supplied under receiver control, limiting scope for denial of service attacks and similar abuse. Since chunks are self-certifying, they can be freely replicated, facilitating caching and bringing significant bandwidth economies. CCN applies to both stored content and to content that is dynamically generated, as in a telephone conversation, for example.

Scientific achievements. RAP is participating in an ANR project named CONNECT which will contribute to the definition and evaluation of RAP is contributing to the design of CCN in two main areas:

— the design and evaluation of traffic controls recognizing that TCP is no longer applicable and queue management will require new, name-based criteria to ensure fairness and to realize service differentiation;
— the design and evaluation of replication and caching strategies that realize an optimal trade-off of expensive bandwidth for cheap memory. With some 96% of Internet traffic currently generated by users retrieving content of one form or another, it is increasingly important to understand the memory bandwidth tradeoff achievable through caching, whether this be performed in content distribution networks overlaid on IP or in radical new Internet architectures like CCN.

We have proposed that CCN traffic control be based on router-imposed fair sharing between flows identified on-the-fly through the object name included in packet headers. A number of features and mechanisms would need to be added to the CCN paradigm to realize the proposed control framework. It is necessary to separately manage short, fast access buffers at router faces and the much larger and slower Content Store. The proposed novel charging scheme, where Interests "buy" Data, ensures adequate return on investment for transmission and storage infrastructure. It defines the appropriate direction of charging, given the receiver-oriented nature of CCN flow control. A simple filtre has been proposed to be implemented in router line cards to perform selective Interest discard as necessary. Simulation of a simple case study shows the effectiveness of the proposed mechanisms and strategies. A more extensive performance evaluation is planned in future work. Preliminary experience in implementing fair queueing and selective Interest discard in the CCx prototype is positive.

Concerning caching strategies, we have first investigated popularity distributions of several types of contents: torrents, VOD ... It turns out that the order of magnitude of the total size of these contents is the petabyte (10^{15} bytes). For this reason, some of the classical results of the literature on the use of cache memories (web servers for example) are not completely relevant in this setting. It turns out that, in this context, the popularity distributions seem to be of the form $n \mapsto K/n^{\alpha}$, $1 \leq n \leq N$ and, *surprisingly*, $\alpha < 1$. The fact that α is less than 1 has an important impact on the performances of caching strategies. The limiting case $\alpha = 0$ corresponds to the uniform distribution on the possible contents, the use of a cache is therefore questionable if its size is only a small fraction of the total size of contents. The performances of caching are analyzed in Fricker et al. [2, 3] below.

For a realistic traffic mix, we have also evaluated in Fricker et al. [3] below the hit rates attained in a two-layer cache hierarchy designed to reduce Internet bandwidth requirements. The model identifies four main types of content, web, file sharing, user generated content and video on demand, distinguished in

terms of their traffic shares, their population and object sizes and their popularity distributions. Results demonstrate that caching VoD in access routers offers a highly favorable bandwidth memory tradeoff but that the other types of content would likely be more efficiently handled in very large capacity storage devices in the core. A lot of work has still to be done in this domain.

Main Publications

[1] Sara Oueslati, James Roberts, and Nada Sbihi. Flow-aware traffic control for a content-centric network. In *Infocom'2012*, 2012. PDF.

[2] Christine Fricker, Philippe Robert, and James Roberts. A versatile and accurate approximation for cache performance. Preprint, February 2012. PDF.

[3] Christine Fricker, Philippe Robert, James Roberts, and Nada Sbihi. Impact of traffic mix on caching performance in a content-centric network. In IEEE, editor, *NOMEN'2012, Workshop on Emerging Design Choices in Name-Oriented Networking*, 2012. PDF.

External support.

— The ANR Project "CONNECT: Content-Oriented Networking: a New Experience for Content Transfer" has begun in January 2011. The lead partner is Alcatel Lucent Bell Labs France and our other partners are INRIA/PLANETE, Orange LAbs, TelecomParisTech, UPMC.

Collaborations. In the context of the CONNECT project, we have extended exchanges with Luca Muscariello, Bruno Kauffmann and Alain Simonian (Orange Labs), Giovanna Carofiglio and Diego Perino (Alcatel-Lucent) and Thomas Bonald and Dario Rossi (Telecom Paris Tech).

We have also held meetings with PARC establishing close cooperation with them and with some participants in the NSF project "Named Data Networking". We also participated in the CCN Community meeting in Palo Alto where we presented our work on traffic control.

Self-Assessment. This prospective work on these new architectures of the Internet is promising. The team has contributed to the development of efficient forwarding strategies and investigate economic arguments that make CCN a viable replacement for IP. The broader problem of the location of contents is naturally a major issue in CCN. Our investigations have shown that the large orders of magnitude of these contents and their slowly decaying popularity distributions have a direct implication on cache sizes and on the algorithms to distribute them.

2.4. **Objective 4, Fundamental Methods: Large Stochastic Networks.**

Personnel.

— Nelson Antunes, Visiting Scientist, University of Algarve
— Mathieu Feuillet INRIA PhD Student, École Polytechnique, corps des Mines
— Christine Fricker INRIA Researcher
— Emanuele Leoncini, INRA PhD Student, University Pierre et Marie Curie
— Hanène Mohamed, Associate Professor University Paris Ouest Nanterre La Défense
— Philippe Robert INRIA Research Director
— James Roberts INRIA Research Director
— Danielle Tibi Associate Professor Paris Denis Diderot

Project-team positioning. This is in some way the toolbox, and the trademark, of the RAP team. The purpose is to investigate scaling methods to analyze the stochastic models associated to network architectures and their algorithms. The corresponding model is generally described by a multi-dimensional Markov jump process for which little can be said: about stability properties or, when it is stable, on its equilibrium. Scaling techniques provide a useful tool to get a first order description of such systems. More specifically, the following scalings were considered during the evaluation period.

— **Mean field convergence.**
The number of nodes of the network converges to infinity and the interaction between two fixed nodes is decreasing to 0. In this case, via a fixed equation, the master equation, one can describe the behavior of a given node and prove the asymptotic independence between nodes.
— **Scaling time and space.**
In this context, the number of nodes is fixed but the time scale of the process is sped up with a scaling factor N and the state $(X(t))$ of the process is scaled by some function $\phi(N)$, i.e. one considers the asymptotic behavior of the *whole* process $(X(Nt)/\phi(N), t \geq 0)$. When N is the norm of the initial state of $(X(t))$ and $\phi(N) = N$, this is the *fluid limit* of the process. If the rescaled process converges to a *simpler* process, like the solution of an ODE, one can expect some qualitative insight on the behavior of the process $(X(t))$.

These have been the main scalings we have analyzed during the evaluation period. We do believe that these tools are fundamental to analyze complex networks.

For these questions the analysis of *interesting* examples still offers the best way to a better understanding of the (sometimes subtle) phenomena associated to scaling in general: existence and uniqueness of limiting processes, characterization of the limits (ODE, random process), stability properties, characterization of the equilibrium, ...

Some of our studies have shown that a *stochastic averaging principle* (SAP) occurs in various situations. In the context of stochastic networks, up to now, loss networks were the main classical examples where this phenomenon arise. It turns out that SAP is more frequent than expected, this is surely one of the topics which should be developed in the coming years.

Scientific achievements.

Mean-Field Scaling.

— Allocation of Multiple Wavelengths in Optical Networks.
In this context N optical network units (ONUs), see Section 2.2 page 5, are visited by S_N servers to transmit their data on a light path. It is assumed the N is large and that S_N/N is converging to some $\gamma > 0$. With the constraints of optical networks, on the number of servers at a given ONU and on the time to allocate a wavelength at an ONU, in the mean-field limit, an ONU is behaving as a queueing system with an intermittent server. Its characteristics are given by the corresponding master equation which is quite simple in this case. See references [4, 6] at page 6.
— Bandwidth Allocation of IP Networks.
In a series of papers, Graham and Robert [8] below and [20] page 18 and Graham et al. [39] page 19, we have investigated a mathematical model of the bandwidth allocation of the algorithm TCP at the level of a network. If the number of papers on the case of ONE node is very large, very few rigorous studies considered the case of a real network, i.e. with more than one node, and several TCP flows going through the nodes. A notable exception is Kelly's work in the domain: it basically states that TCP allocates the bandwidths to the various flows which are the solution of an optimization problem with a convenient utility function. If this approach has been widely

applied in various situations, the basic assumption is not really explained: why should TCP solve an optimization problem ? In our work, we started with the basic principle of TCP which increases linearly throughput and decreases multiplicatively when congestion occurs. By using a mean-field result where the number of flows for each class of TCP connections goes to infinity, we have shown that, at equilibrium, the vector of bandwidths is the solution of a fixed point equation. Our convergence result is therefore a rigorous justification that Kelly's assumption is valid if one considers that the solution of an optimization problem is a zero of the gradient of the utility function.

— Bandwidth Allocation of mobile Networks.
This is the model of a mobile network where communications are aborted when they enter in cell whose capacity is fully utilized. By assuming a large number of cells and a completely connected network, the mean-field limit of the network is a dynamical system in a complicated state space. The main result of Antunes et al. [11] below is the fact that, in some situations, there are several stable points for the dynamical system. This is the first rigorous result of metastability for stochastic networks.

— Allocation of Resources for bike sharing systems.
In these networks, users take a bike at the closest station and leaves at the station near its destination. The general problem of these systems is of allocating bikes to the convenient stations so that most of users will find a bike when necessary. To investigate the efficiency of bike sharing systems in a urban network with finite capacity stations (only a finite number of bikes at a given station), a mean-field approach has been used, by letting the number of stations go to infinity. In this context one obtains the expression of the limit of the stationary distribution of the number of bikes at a given station. It gives a qualitative measure of the efficiency of the resource allocation. See Fricker and Gast [49] page 20. The technical tool to prove these results is a convenient Lyapunov function, as in Antunes et al. [11] and Tibi [54], it is expressed as a relative entropy plus a complementary term.

Times Scales of Stochastic Networks.

— Reliability of distributed storage system.
A set of N servers may accommodate a subset of $F_N \sim \beta N$ files. Each file can be duplicated on d different servers. Each file is lost at rate μ. A file without any copy is lost for good. The system has a total capacity λN to copy files on servers. The system can be represented by a transient Markov process which dies when all files are lost. When $d = 2$ (two copies at most) we have shown that if $\lambda > 2\beta\mu$, then the network does not loose a significant fraction of its files in the following sense:
  – on the time scale $t \to t/N$, with probability one, no file is lost on this time scale,
  – on the time scale $t \to t$ the number of lost files at time t is Poisson.

  But
  – on the time scale $t \to Nt$, the fraction $\psi(t)$ of lost files at "time Nt" is the solution of some fixed point equation. In this case an interesting *stochastic averaging principle* occurs.

  See reference Feuillet and Robert [51] at page 20.

— Bandwidth allocation in networks without congestion control.
In this context, all sources transmit at their maximum rate (instead of using a TCP-like scheme) and recover from packet loss by the use of some ideal erasure coding scheme. The efficiency of resource utilization in terms of the maximum load the network is analyzed with fluid limits to determine its stability region. Contrary to usual models, the bandwidth allocation is determined by the packet dropping policy in routers. It has been shown that the stability region is optimal for the so-called Fair Dropping policy. On the contrary, this is not the case for the Tail-Dropping policy which is used in most routers. However, in some topologies, the stability region is near optimal if the maximum rate of users is sufficiently small compare to links capacity. Additionally, in the fluid scaling, an averaging principle is shown to occur for some network topologies. See reference [1] below.

— Scaling Analysis of a Pagerank Algorithm.
In this studies, the system is described by a null recurrent Markov process, to investigate the asymptotic behavior of these processes is investigated via unconventional time scales. See [3] below.

Branching Processes. We used these processes in two different modeling studies. The first one is a sequel on mathematical models of peer to peer systems started in the previous evaluation period. A file is split into several pieces called chunks. The general simple principle is that once a node has retrieved a chunk, it in turn becomes a server for this chunk. In Robert and Simatos [9] below we studied the initial phase when a new content is present in the network, limit results with several time scales for spaces give an asymptotic description of the file diffusion. We have considered in Leskelä et al. [5] below a stochastic model for chunk arrival times and download durations. The maximal arrival rate that such a network can accommodate has been determined, i.e., the conditions under which the Markov process describing this network is ergodic. Technical estimates related to the survival of interacting branching processes are key ingredients to establish the stability of these systems.

The second model where a branching procedure occurs is in the PhD work of E. Leoncini, in collaboration with INRA, on the production of proteins within a bacterium. Such organism devotes more than 80% of its resources to this production. There are around 2000 protein types which co-exist inside with various, *fixed*, concentration. Because of the intrinsic disorder of the cell, there must be some randomness (the cell cannot count...) and the main problem is to identify the key parameters of the bacterium which have an impact on the variance of the number of proteins produced. This is a key question to understand the economy of these cells. Up to now, only Markovian tools have been used, but the duration of some of the internal processes cannot be exponentially distributed. We used and developed a technique used in loss networks to give an explicit expression of the variance of the protein production. Curiously, our first results seem to show that classical results of the literature (with exponential assumption) may significantly underestimate the variance.

Main Publications

[1] Mathieu Feuillet. On the flow-level stability of data networks without congestion control: the case of linear networks and upstream trees. *Queueing Systems, Theory and Applications*, 70(2) 105–143, 2012. PDF.

[2] Mathieu Feuillet and Philippe Robert. On the transient behavior of Ehrenfest and Engset processes. *Advances in Applied Probability*, 44(2), 2011 PDF.

[3] Nelly Litvak and Philippe Robert. A scaling analysis of a cat and mouse Markov chain. *Annals of Applied Probability*, 2012. To Appear, PDF.

[4] Florian Simatos and Danielle Tibi. Spatial homogenization in a stochastic network with mobility. *The Annals of Applied Probability*, 20(1):312–355, 2010. PDF.

[5] Lasse Leskelä, Philippe Robert, and Florian Simatos. Interacting branching processes and linear file-sharing networks. *Advances in Applied Probability*, 42(3):834–854, 2010. PDF.

[6] Philippe Robert. The evolution of a spatial stochastic network. *Stochastic Processes and Applications*, 120(7):1342–1363, 2010. PDF.

[7] Hanène Mohamed and Philippe Robert. Dynamic tree algorithms. *Annals of Applied Probability*, 20(1):26–51, 2010. PDF.

[8] Carl Graham and Philippe Robert. Interacting multi-class transmissions in large stochastic networks. *Annals of Applied Probability*, 19(6):2334–2361, 2009. PDF.

[9] Philippe Robert and Florian Simatos. Occupancy schemes associated to Yule processes. *Advances in Applied Probability*, 41(2):600–622, 2009. PDF.

[10] Christian Gromoll, Philippe Robert, and Bert Zwart. Fluid limits for processor sharing queues with impatience. *Mathematics of Operations Research*, 33(2):375–402, May 2008. PDF.

[11] Nelson Antunes, Christine Fricker, Philippe Robert, and Danielle Tibi. Stochastic networks with multiple stable points. *Annals of Probability*, 36(1):255–278, 2008. PDF.

Collaborations. For this topic, we had several co-authors from other research centers:

Thomas Bonald Telecom Paris Tech
Nicolas Gast, EPFL, Lausanne,
Christian Gromoll, University of Stanford,
Nelly Litvak, University of Twente,
Amandine Véber, École Polytechnique,
Bert Zwart, CWI, Amsterdam.
Vincent Fromion, INRA,
Carl Graham, École Polytechnique,
Lasse Leskelä, University of Helsinki,
Alexandre Proutière, Microsoft,
Maaike Verloop, University of Eindhoven,

Self-Assessment. During this evaluation period, the scaling techniques have proved to be extremely useful to investigate the performances of various systems: optical networks, attack detection algorithms, bandwidth allocation in IP networks and in mobile networks, reliability of distributed storage systems, resource allocation algorithms in various situations like bike sharing systems, pagerank algorithms,... This is a good illustration of the power of these methods. Furthermore, these studies lead us to an analysis of new stochastic averaging problems occurring in an unusual context for stochastic networks.

3. Knowledge dissemination

Publications. Concerning journals, the main targets for the project-team RAP are the following journals: "Annals of Applied Probability" and "Advances in Applied Probability". Occasionally other journals can be targeted like "Stochastic Processes and Applications", "Mathematics of Operation Research", "Random Structures and Algorithms" or "Queueing Systems". An effort is also made to contribute to some of the conferences on networks.

	year1	year2	year3	year4
PhD Thesis		2		
Journal	3	4	9	7
Conference proceedings	4	2	6	4
Book				1
Patent				1
General audience papers		1		

Journals.

- Annals of Applied Probability: 4
- Advances in Applied Probability: 3
- Queueing Systems, Theory and Applications: 6
- Annals of Probability: 1.
- Mathematics of Operations Research: 1.
- Random Structures and Algorithms: 1.
- Stochastic Processes and Appl.: 1.

Conferences.

- ACM Sigmetrics: 4
- INFOCOM: 2
- ITC Specialist Seminar on Internet Traffic Engineering and Traffic Management: 3

Software and Valorization and technology transfer. The RAP team focus on the design of efficient algorithms for communication networks. During this evaluation period, we had to develop prototypes to validate several of our algorithms.

- *Attack detection software.*
  It has been written during Yousra Chabchoub's PhD thesis in collaboration with Stéphanie Motteau at Orange Labs. It has been tested on real traffic at Orange labs in Lannion.
- *Simulator for a PON.*
  This simulator has been extensively used to test and validate the algorithm of bandwidth allocation.
- *Forwarding strategies in CCN networks.*
  Algorithms to control the rate of transmission of interests in a CCN have been implemented on a Linux box, a module in the Linux kernel has been modified to test them.

We do not intend to develop and maintain a particular software. Our strategy is of developing a prototype and transfer it to our industrial partner.

Patent

[1] Raluca-Maria Indre, Esther Le Rouzic, and James Roberts. Multipaths optiques pour la construction d'un WAN passif, 2011. Patent n°11 55619.

Teaching.

- Mathieu Feuillet is teaching assistant for the course "Traffic, Queueing and Networks" given by Thomas Bonald at Telecom ParisTech. 18h.
- Emanuele Leoncini is teaching assistant at the University Pierre et Marie Curie. 16h.
- Philippe Robert is at
  - École Polytechnique. Undergraduate lectures on stochastic modeling of communication networks. 50h.
  - University Pierre et Marie Curie. Lectures at Master level on the analysis of probabilistic algorithms. 18h.

— James Roberts lectured to third year students at Telecom ParisTech on "Traffic management and the future Internet".

General Audience Actions. Philippe Robert has given general presentations for students of high schools level and, separately, to their professors.

High schools (Lycées in French). The subjects of these talks are on the mathematical models of communication networks and also of their associated algorithms: TCP, bandwidth allocations problems, how Google search algorithm works, ...

2008. Lycée Camille See (Paris). Classes de Seconde.
2009. Lycée Jeanne d'Albret (Saint Germain en Laye). Classes de Première.
2011. Lycée Rosa Parks (Montgeron). Classes de Première.

Concerning professors, at the occasion of a change of program in mathematical classes of high schools (introduction of the notion of algorithm for example), talks were designed around various examples of algorithms to show, in particular, that an algorithm is NOT only a numerical procedure.

2009. Professors of IUFM of the academy of Versailles.
2009. Inspectors de mathematics of Créteil, Rennes, Lille, la Guyane et la Réunion academies.
2010. Conference at the "Maths Club" of IREM at the University Paris denis Diderot for students of the first two years.
2010. Professors of mathematics of Lycées of the Academy of Versailles.

An introductory paper on stochastic modeling of communication networks has been published in the French edition of "Scientific American".

Publication

[1] Philippe Robert. 1909-2009, l'odyssée des réseaux. In *L'ère d'Internet*, number 66 in Dossiers Pour la Science, pages 42–49. Pour la Science, Janvier-Mars 2010. Survey paper for French Edition of Scientific American. PDF.

Visibility.

— Mathieu Feuillet
  – Fondation Telecom prize for his internship work at Microsoft Research and Orange Labs in 2008-2009.
— Christine Fricker
  – Member of the jury of "Agrégation de Mathématiques" 2012.
— Philippe Robert
  – Associate Professor at the École Polytechnique in the department of applied mathematics.
  – Associate Editor of the Book Series "Mathématiques et Applications" edited by Springer Verlag.
  – Associate Editor of the journal "Queueing Systems, Theory and Applications"
  – Member of the scientific council of EURANDOM in Eindhoven.
  – Plenary Conference "*Scaling methods for the analysis of stochastic networks*" of Applied Probability Society Conference of INFORMS, Stockholm, July 2011.
  – Member of the evaluation committee (6 members) in 2009 of the Applied Mathematics programs of three Dutch Universities (Delft, Eindhoven, and Twente) over the period 2003-2008.
  – Member of the jury "ANR blanc" in mathematics in 2010.
  – Technical Program Chair (TPC) of the conference Performance'2011 (with Gil Zussman).
  – TPC member for ACM Sigmetrics 2010, ACM Sigmetrics 2011, ITC'21, ITC'22 and Performance 2010.
— James Roberts
  – co-organized the workshop EuroNFTraf09 on Traffic management and traffic engineering for the future Internet (7-8 December).
  – Fellow (membre émérite) of the SEE in November 2009.
  – TPC member for Infocom 2010, Infocom 2011, Infocom WiP workshop, ICC'11, CQRM, ONDM 2010, ONDM 2011, ITC 22, ITC Specialist Seminar on Multimedia Applications, Performance'2011.

4. External Funding

National initiatives			
RNRT OSCAR		2006-2008	50k€
ANR SADA		2005-2008	79k€
ANR CONNECT		2011-2012	176k€
Industrial contracts			
CRE Orange Labs		2009-2011	145k€
CRE Orange Labs		2012-2013	75k€
Scholarships			
PhD	Grant from INRA	2010-2013	110k€

General Comment. As it can be seen our funding is coming from two main sources: National funding (ANR) and industrial funding with our regular collaboration with Orange Labs.

National initiatives.

- Participation to the RNRT project "OSCAR" on the attack detection in the Internet. Two years contract starting from April 2006. Participants: ENS Lyon, Get, INRIA, France Telecom, Laas, LIP6.
- Participation to the ANR Projet Blanc "SADA" on the Discrete Random Structures, three year contract starting from 2005. Participants: University of Bordeaux, University of Caen, Computer science department of École Polytechnique, INRIA Algo and Rap projects, University of Versailles.
- ANR Project "CONNECT: Content-Oriented Networking: a New Experience for Content Transfer". The proposal submitted to the VERSO programme has been accepted. The planned starting date is January 2011 and the project is scheduled to last 2 years. The lead partner is Alcatel Lucent Bell Labs France and the other partners are RAP, INRIA/PLANETE, Orange LAbs, TelecomParisTech, UPMC.

European projects. No funding during the evaluation period from this source.

The team is currently participating to two recent European project proposals.

- CELTICS-Plus "SASER".
- FP7 "Scot".

See Section 5.

Industrial contracts.

- CRE contract "Algorithmes d'allocation de ressources dans les réseaux optiques" with Orange Labs on bandwidth allocation algorithm in optical networks. Two years starting from 2009.
- CRE with Orange Labs " Dynamical Optical Networking in the Internet". Contract on bandwidth allocation algorithm in optical networks. Duration 2 years starting from 01/01/12.

5. Objectives for the next four years

As it has been seen, the two activities on optical networks and on content centric networks are quite recent. We intend to continue to develop and extend our initial investment in these promising domains, with a slight broadening of the scope in the case of CCN. Concerning methodological tools, we plan a more systematic study of mean field results and of stochastic averaging principles.

Optical Networks. While we have found considerable promise in the use of passive optical components, it is necessary to recognize that alternative dynamic optical technologies may also play an important future role in the Internet. It is important, for example, to evaluate the potential of optical burst switching and optical packet switching as replacements for electronic routers. Similarly, dynamic optical circuit switching or optical flow switching may be particularly useful for the transport of large objects in a future information-centric network. In future, it may prove necessary to study algorithms and mechanisms that usefully combine passive and active optical technologies of various types.

The proposed research will build on the above results to propose algorithms to control resource sharing in the Internet using dynamic optical technology. The focus is principally on the use of passive optical components since these appear to be the most cost effective and are already feasible but the integration of alternative optical packet, burst and flow switching approaches will be envisaged. Specific objectives of the investigations include the following.

(1) Further elaboration of the multipoint-to-multipoint lightpath structure and its use to create a passive optical mesh network in replacement of the current core of high capacity electronic routers.
(2) Performance evaluation of the optical mesh relating capacity and performance under a realistic demand model.
(3) Application of optical technology in a future information-centric network where active and passive components are combined to realize efficient content dissemination.

We have participated in the preparation of a European CELTICS+ project proposal with Alcatel-Lucent, Orange Labs, Telecom Paris Tech, Fujitsu Semiconductor Europe and others. It includes a work package dedicated to the development and experimentation of the network proposed in Indre et al [1] of Section 2.2.

Information Centric Networks. The investigation of so-called information-centric networking (ICN) architectures is bringing a renewed interest in the performance of caching. It is particularly important to understand the potential for trading off bandwidth for memory by implementing a network of caches and to develop tools that enable the optimization of such a network. The ICN application places particularly stringent requirements on evaluation tools since the population of content items available via the Internet is immense and caches are required to store content of diverse types, each type being distinguished by its peculiar popularity characteristics.

Concerning caching strategies, we plan to pursue our investigations in the following directions:

— Design and evaluate a global architecture of ICN with data centers.
— Study the performances of caching strategies in a hierarchical architecture.
Despite it has already received and still receives a lot of attention, the benefit of a hierarchical organization of caches in an ICN architecture is still not properly understood. The large order of magnitude of the sizes of data to store is a new element added to this classical problem, but this is not the only difficulty. In an heterogeneous context, different types of contents may be mixed in the upper parts of the caching architecture: the impact of this phenomenon on caching policies is unknown.

Data on popularity distributions. This is not an easy task. In the past evaluation period we had to dig out some data from torrent web sites such as *http://www.demonoid.me*. This is, in our view, not completely satisfactory. Interesting sites such as *youtube.com* provide mainly a kind of cumulated popularity (over the years), it has little interest from the point of view of caching strategies, only current popularity is a meaningful information. An effort has certainly to be done in this domain.

We have participated in the preparation of a European FP7 project "Scot" proposal with Alcatel-Lucent, Alcatel-Lucent Bell, the University of Oslo, Institut Télécom, Simula Research Laboratory AS, University of Gent, Université of Pau, CWI (Amsterdam), Université Libre de Bruxelle and Technische Universiteit Eindhoven. Our participation concerns the investigation of caching strategies in ICN networks. A collaboration with INRIA team maestro should take place in the next evaluation period.

Large Stochastic Networks.

Mean-Field Scalings. Up to now, there is a significant corpus of methods to prove mean field results. During the past evaluation period, we have seen that the convergence on finite time intervals can be established without too much trouble, provided that the limiting dynamical system is sufficiently regular and that some topological questions are solved. The same is not true when one considers the equilibrium of the sequence of scaled processes. The key ingredient is a compactness result of these invariant distributions which is not easy to prove in general. Except in special cases where monotonicity properties hold. This is not the case for some of the optical architectures we considered for example. Another important problem in this domain is of characterizing the convergence to the fixed points of the mean-field limit. It gives a quantitative description of the attraction of the fixed point. A possible tool is of using a convenient Lyapounov function. It turns out that guessing such a function is not an easy task. It has been done in reference Antunes et al. [15] page 18 and Tibi [54] page 20 and in the work on the bike sharing system.

In the next evaluation period, these questions will be considered for the following models

- Bike sharing system performance. We intend to investigate the impact of the redistribution of bikes by dedicated trucks. The mean-field picture is also challenging if one takes into account the geometry of the network and also of the heterogeneity of the stations.
- Bandwidth allocation in optical networks. An open problem is the convergence of the invariant distributions for polling systems with several classes of servers together with a characterization of this limit.
- Mean-field picture of the evolution of the respective numbers of proteins within the bacterium. The purpose is to describe the interaction of production mechanisms of different classes of proteins and the optimal use of the resources in this context.

Interaction of time scales. As already mentioned, we encountered unexpected stochastic averaging principles (SAP), see reference Feuillet and Robert [51] page 20 for example. A bandwidth allocation algorithm studied with Amandine Veber (École Polytechnique) exhibits also a SAP. Our goal is, for the next period, of completing the work done on stochastic networks with failure described page 10, in particular when there are $d > 2$ possible copies for each file.

Because of the various technical difficulties we encountered, we plan to investigate general questions related SAP. Basically, in its simplest setting, the phenomenon is as follows: the Markov process has at least two components: one which evolves on a fast time scale and the other on the "normal" time scale, the inter-dependence of these two dynamics makes the complexity of these questions. This is quite well known for loss networks but up to now, there were few other examples. If it is not uncommon that time scales interact in stochastic networks, the dependence is in general in one-way: "slow" coordinates depend on the "fast" ones until the repartition slow/fast changes. In the case of a SAP, this is a two-way dependence and there is a continuum of Markov processes indexed by the slow process. See Freidlin and Wentzell (1993) or Kurtz (1994) for example.

In the examples we have investigated, we found that the technical tools usually used in the literature suffer from two shortcomings:

- Some of them seem to be unnecessary complicated, to prove a convenient compactness properties of the random measures associated with the fast times scales for example. This adds a really technical part to the analysis.
- Some proofs of a SAP seem to be incomplete, the main problem being of controlling the continuum of invariant distributions when the scaling parameter goes to infinity.

If the first point raises difficult topological problems, the second point seems to be even more delicate. It can be done when the model has a useful monotonicity property. Unfortunately this is far from being true in general. This has to be investigated more thoroughly.

As a general conclusion, the identification of the various time scales that drive the evolution of stochastic networks is, in our view, *a major research topic.*

6. Bibliography of the project-team

Books and Monographs.

[1] Thomas Bonald and Mathieu Feuillet. *Network Performance Analysis*. ISTE/Wiley, july 2011. HTTP.

Doctoral dissertations.

[2] Yousra Chabchoub. *Analyse et modélisation du trafic Internet*. PhD thesis, Université Pierre et Marie Curie, October 2009. PDF.

[3] Florian Simatos. *Étude de modèles probabilistes de réseaux pair-à-pair et de réseaux avec mobilité*. PhD thesis, École Polytechnique, December 2009. PDF.

Articles in referred journals: Probability.

[4] Mathieu Feuillet and Philippe Robert. On the transient behavior of Ehrenfest and Engset processes. *Advances in Applied Probability*, 44(2), 2011. To Appear. PDF.

[5] Nelly Litvak and Philippe Robert. A scaling analysis of a cat and mouse Markov chain. *Annals of Applied Probability*, 2011. To Appear. PDF.

[6] Nelson Antunes and Vladas Pipiras. Probabilistic sampling of finite renewal processes. *Bernoulli Journal*, 2010. PDF.

[7] Florian Simatos and Danielle Tibi. Spatial homogenization in a stochastic network with mobility. *The Annals of Applied Probability*, 20(1):312–355, 2010. PDF.

[8] Lasse Leskelä, Philippe Robert, and Florian Simatos. Interacting branching processes and linear file-sharing networks. *Advances in Applied Probability*, 42(3):834–854, 2010. PDF.

[9] Philippe Robert. The evolution of a spatial stochastic network. *Stochastic Processes and Applications*, 120(7):1342–1363, 2010. PDF.

[10] Hanène Mohamed and Philippe Robert. Dynamic tree algorithms. *Annals of Applied Probability*, 20(1):26–51, 2010. PDF.

[11] Carl Graham and Philippe Robert. Interacting multi-class transmissions in large stochastic networks. *Annals of Applied Probability*, 19(6):2334–2361, 2009. PDF.

[12] Philippe Robert and Florian Simatos. Occupancy schemes associated to Yule processes. *Advances in Applied Probability*, 41(2):600–622, 2009. PDF.

[13] Fabrice Guillemin and Philippe Robert. Analysis of Steiner subtrees of random trees for traceroute algorithms. *Random Structures and Algorithms*, 35(2):194–215, September 2009. PDF.

[14] Christian Gromoll, Philippe Robert, and Bert Zwart. Fluid limits for processor sharing queues with impatience. *Mathematics of Operations Research*, 33(2):375–402, May 2008. PDF.

[15] Nelson Antunes, Christine Fricker, Philippe Robert, and Danielle Tibi. Stochastic networks with multiple stable points. *Annals of Probability*, 36(1):255–278, 2008. PDF.

Articles in referred journals: Stochastic Models.

[16] T. Bonald and M. Feuillet. Performance of CSMA in multi-channel wireless networks. *Queueing Systems: Theory & Applications*. To appear.

[17] Thomas Bonald and James Roberts. Internet and the Erlang formula. *ACM SIGCOMM CCR*, 2011. To Appear. PDF.

[18] Ed Coffman, Philippe Robert, Florian Simatos, Shuzo Tarumi, and Gil Zusman. A performance analysis of channel fragmentation in dynamic spectrum access systems. *Queueing Systems, Theory and Applications*, 2011. To Appear.

[19] Mathieu Feuillet. On the flow-level stability of data networks without congestion control: the case of linear networks and upstream trees. *Queueing Systems, Theory and Applications*, 70(2):105–143, 2012. PDF.

[20] Carl Graham and Philippe Robert. Self-adaptive congestion control for multi-class intermittent connections in a communication network. *Queueing Systems, Theory and Applications*, 69(3):237–257, 2011. PDF.

[21] Nelson Antunes, Christine Fricker, and James Roberts. Stability of multi-server polling system with server limits. *Queueing Systems, Theory and Applications*, 68(3-4):229–235, 2011. PDF.

[22] Philippe Robert and James Roberts. A mean field approximation for the capacity of server-limited, gate-limited multi-server polling systems. *SIGMETRICS Performance Evaluation Review*, 38(2):24–26, 2010. HTTP.

[23] Yousra Chabchoub, Christine Fricker, Fabrice Guillemin, and Philippe Robert. On the statistical characterization of flows in internet traffic with application to sampling. *Computer Communications*, 33(1):103–112, 2010. PDF.

[24] Thomas Bonald and Mathieu Feuillet. On the stability of flow-aware CSMA. *Performance Evaluation*, 67:1219–1229, November 2010. PDF.

[25] Christine Fricker, Fabrice Guillemin, and Philippe Robert. An identification problem in an urn and ball model with heavy tailed distributions. *Probability in the Engineering and Informational Sciences*, 24(1):77—97, 2010. PDF.

[26] Christine Fricker, Fabrice Guillemin, and Philippe Robert. Perturbation analysis of an $M/M/1$ queue in a diffusion random environment. *Queueing Systems, Theory and Applications*, 61(1):1–36, 2009. PDF.

[27] Yousra Chabchoub, Christine Fricker, Fabrice Guillemin, and Philippe Robert. Inference of flow statistics via packet sampling in the internet. *IEEE Communications Letters*, 12(12):897 — 899, 2008. PDF.

Publications in Conferences and Workshops.

[28] Sara Oueslati, James Roberts, and Nada Sbihi. Flow-aware traffic control for a content-centric network. In *Infocom'2012*, 2012. PDF.

[29] Christine Fricker, Philippe Robert, James Roberts, and Nada Sbihi. Impact of traffic mix on caching performance in a content-centric network. In IEEE, editor, *NOMEN'2012, Workshop on Emerging Design Choices in Name-Oriented Networking*, 2012. PDF.

[30] Thomas Bonald and Mathieu Feuillet. On flow-aware CSMA in multi-channel wireless networks. In *CISS*, march 2011.

[31] Philippe Robert and James Roberts. A flow-aware MAC protocol for a passive optical metropolitan area network. In *23th ITC Specialist Seminar on Internet Traffic Engineering and Traffic Management*, San Francisco, 2011. PDF.

[32] Nelson Antunes, Gonçalo Jacinto, and António Pacheco. An analytical framework to infer multihop path reliability in MANETs. In *ACM-Sigmetrics*, New-York, June 2010. ACM.

[33] Nelson Antunes, Christine Fricker, Philippe Robert, and James Roberts. Gate-driven dynamic bandwidth allocation for WDM EPON. In *GLOBECOM 2010*, Miami, 2010. IEEE Communications Society. PDF.

[34] Nelson Antunes, Christine Fricker, Philippe Robert, and James Roberts. Traffic capacity of large WDM passive optical networks. In *22th ITC Specialist Seminar on Internet Traffic Engineering and Traffic Management*, pages 333–344, Amsterdam, September 2010. IEEE Communications Society. PDF.

[35] Ed Coffman, Philippe Robert, Florian Simatos, Shuzo Tarumi, and Gil Zusman. Channel fragmentation in dynamic spectrum access systems. In *ACM-Sigmetrics*, New-York, June 2010. ACM. PDF.

[36] Ayalvadi Ganesh, Sarah Lilienthal, D. Manjunath, Alexandre Proutière, and Florian Simatos. Load balancing via random local search in closed and open systems. In *ACM-Sigmetrics*, New-York, June 2010. ACM. DOI.

[37] Mathieu Feuillet, Alexandre Proutière, and Philippe Robert. Random capture algorithms: Fluid limits and stability. In *Information Theory and Applications Workshop*, February 2010. PDF.

[38] Thomas Bonald, Mathieu Feuillet, and A. Proutière. Is the law of the jungle sustainable for the Internet? In *Proceedings of INFOCOM*, 2009. PDF.

[39] Carl Graham, Philippe Robert, and Maaike Verloop. Stability properties of networks with interacting TCP flows. In *Proceedings of NET-COOP*, Eindhoven, November 2009. Springer Verlag. PDF.

[40] Yousra Chabchoub, Christine Fricker, and Hanène Mohamed. Analysis of a bloom filter algorithm via the supermarket model. In *Proceedings of ITC21*, September 2009. PDF.

[41] Nelly Litvak and Philippe Robert. Analysis of an on-line algorithm for solving large markov chains. In *The 3rd International Workshop on Tools for solving Structured Markov Chains*, Athens, October 2008. ACM.

[42] Carl Graham and Philippe Robert. A multi-class mean-field model with graph structure for TCP flows. In *Proceedings of European Consortium For Mathematics In Industry 2008*, London, June 2008. Springer.

[43] Florian Simatos, Philippe Robert, and Fabrice Guillemin. A queueing system for modeling a file sharing principle. In *ACM-Sigmetrics*, Annapolis, June 2008. ACM/IFIP WG 7.3. PDF.

[44] Yousra Chabchoub, Christine Fricker, Frédéric Meunier, and Danielle Tibi. Analysis of an algorithm catching elephants on the Internet. In *Fifth Colloquium on Mathematics and Computer Science*, DMTCS Proceedings Series, pages 299–314, september 2008. PDF.

[45] Florian Simatos. A variant of the Recoil-Growth algorithm to generate multipolymer systems. In *Proceedings of the Fifth Colloquium on Mathematics and Computer Science, Blaubeuren*, 2008. PDF.

Patent.

[46] Raluca-Maria Indre, Esther Le Rouzic, and James Roberts. Multipaths optiques pour la construction d'un WAN passif, 2011. Patent n°11 55619.

General Presentation.

[47] Philippe Robert. 1909-2009, l'odyssée des réseaux. In *L'ère d'Internet*, number 66 in Dossiers Pour la Science, pages 42–49. Pour la Science, Janvier-Mars 2010. Survey paper for French Edition of Scientific American — PDF.

Preprints.

[48] Nicolas Gast Christine Fricker and Hanène Mohamed. Mean field analysis for inhomogeneous large bike-sharing systems. submitted, February 2012.

[49] Nicolas Gast Christine Fricker. Incentives and regulations in bike-sharing systems with stations of finite capacity. Preprint. PDF, February 2012.

[50] Christine Fricker, Philippe Robert, and James Roberts. A versatile and accurate approximation for cache performance. Preprint: PDF, February 2012.

[51] Mathieu Feuillet and Philippe Robert. The time scales of a stochastic network with failures. Preprint, 2012.

[52] Mathieu Feuillet, Matthieu Jonckheere, and Balakrishna J. Prabhu. Responding to traffic surges: Stochastic networks under time-space-priority scalings. submitted. PDF, 2011.

[53] Davide Cuda, Raluca-Maria Indre, Esther Le Rouzic, and James Roberts. Getting routers out of the core: Building an optical wide area network with "multipaths". submitted. PDF, 2011.

[54] Danielle Tibi. Metastability in communication networks. Preprint. PDF, 2010.