INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Trec

Network Theory and Communications

Rocquencourt

THEME COM

Activity Report

2006

Table of contents

1. Team

TREC is a joint INRIA-ENS project-team.

Head of project team
François Baccelli [Research Director (DR1) INRIA, HdR]

Vice-head of project team
Bartłomiej(Bartek) Błaszczyszyn [Research Associate (CR1) INRIA]

Administrative assistant
Florence Barbara [Secretary (AI) INRIA]
Laurence Lenormand [Secretary (*poste contractuel à temps partiel (50%) sur le projet*) INRIA]

Staff member
Marc Lelarge [Research Associate (CR2) INRIA, since November 2006]

Scientific adviser
Pierre Brémaud [HdR]

Research scientist
Thomas Bonald [Research engineer, France Télécom R&D until August 2006]
Alexandre Proutière [Research engineer, France Télécom R&D, until August 2006]

Post-doctoral fellow
Božidar Radunović [supported by the Ministry of Research, until October 2006]
Prasanna Chaporkar [supported by the European Research Consortium for Informatics and Mathematics (ERCIM), until August 2006]
Vivek Mhatre [supported by Thomson, since June 2006]

Ph. D. Students
Charles Bordenave [École Polytechnique and Corps des Télécoms until October 2006, visiting the University of Ottawa in November 2006, postdoc at the University of California at Berkeley since December 2006]
Giovanna Carofiglio [ENS and Politcenico di Torino, since March 2006]
Augustin Chaintreau [ENS and Corps des Télécoms until January 2006, researcher at the Thomson Paris Lab since October 2005]
Bruno Kauffmann [ENS, since September 2006]
Julien Reynier [ENS and Corps des Télécoms, until October 2006, working for Motorola Saclay since November 2006]
Perla Sousi [Cordi INRIA, since October 2006]
Minh Anh Tran [École Nationale Supérieure des Télécommunications]

Visiting Scientist
Venkat Anantharam [Berkeley University, USA]
Serguei Foss [Heriot-Watt University, Edinburgh, UK]
Henri Koskinen [Helsinki University of Technology, Finland]
Hermann Thorisson [University of Iceland, Iceland, with TREC from July to August 2006]

Intern Students
Marta Piancino [Politecnico di Torino, Italy, with TREC from March to August 2006]
Yogeshwaran Dhandapani [Indian Institute of Science, India, with TREC from May to July 2006]

2. Overall Objectives

2.1. Overall Objectives

TREC is a joint INRIA-ENS project-team. It is focused on the modeling and the control of communication networks. Its methodological activities are combined with projects defined with industrial partners, notably Thomson, Alcatel, France Télécom, Intel and Sprint. The main research directions are :

- communication network control: admission control, flow regulation, congestion control, traffic analysis in controlled networks;
- modeling and performance analysis of wireless networks (cellular, WLAN's, ad-hoc): coverage and load analysis, power control, evaluation and optimization of the transport capacity, self organization;
- stochastic network dynamics, in particular by means of algebraic methods, with a main emphasis on rare events and large network asymptotics;
- the development of mathematical tools based on stochastic geometry, random graphs and spatial point processes: Voronoi tessellations, coverage processes, random spatial trees, spectral analysis, Gibbs fields.

3. Scientific Foundations

3.1. Scientific Foundations

Here is the scientific content of each of the four main research directions.

- Modeling and control of communication networks. Here we mean control of admission, flow regulation and feedback control *à la TCP*, the understanding and improvements of which are major challenges within the context of large networks. Our aim is a mathematical representation of the dynamics of the most commonly used control protocols, from which one could predict and optimize the resulting end user bandwidth sharing and QoS. The design of scalable simulators that could be used for the dimensioning of large IP networks is a first practical outcome of this line of research. We currently try to use our better understanding of the dynamics of these protocols on such structures as 1) Internet multicast overlays and 2) TCP proxies (also known under the name of Split TCP or TCP splicing) as used in wireless access networks.
- Modeling and performance analysis of wireless networks. The main focus is on the following three classes of wireless networks: cellular networks, mobile ad hoc networks (MANETs) and Wifi mesh networks.

  Concerning cellular networks, a new mathematical representation of interferences based on shot-noise has led to a variety of results on coverage and capacity of large CDMA networks when taking into account intercell interferences and power control. The mathematical analysis of the interference and power control problems allowed for the definition of new decentralized admission and congestion control protocols. The interest in these algorithms, besides their potential pertinence for network operators, comes from the fact that they allow for explicit evaluation of several macroscopic characteristics of the network. Our general goal is to propose a strategy for the densification and parameterization of UMTS networks that is optimized for both voice and data traffic.

  Using a similar approach, in particular additive and extremal shot-noise processes, we currently investigate also MAC layer scheduling algorithms and power control protocols for MANETs. We concentrate on cross layer optimizations allowing one to maximize the transport capacity for multihop MANETs. A recent example within this class of problems is the concept of opportunistic routing for MANETs that we currently study with the Hipercom project team of Rocquencourt.

  We also continue the line of thoughts on the self-organization of Wifi mesh networks. The general problem within this context is to find robust and fully distributed algorithms for the selection of channels by access points and for the association of users to access points. We proposed and analyzed a new class of such algorithms based on Gibbs' sampler.
- Theory of network dynamics. TREC strongly contributed to the development of new directions of research in queueing theory. The main directions investigated this year concern extensions of product form theory and of the theory of insensitivity within the context of the new bandwidth sharing paradigms that have been proposed in the literature lately.

TREC is also pursuing the elaboration of a stochastic network calculus, that would allow the analysis of network dynamics by algebraic methods. The mathematical tools are those of discrete event dynamical systems: semi-rings (max, plus) and inf-convolutions, as well as their non linear extensions (topical and non expansive maps, monotone separable framework); the main probabilistic tools within this framework are ergodic theory, asymptotic analysis, Lyapounov exponent analysis, perturbation analysis and large deviations. The main current contributions bear on the analysis of rare events within this framework.

- Stochastic geometry and the theory of point processes. The theory of point processes on the real line plays a key role in teletraffic analysis. The main mathematical tools studied within this framework are Palm calculus, stochastic intensity and Gibbs fields. Stochastic geometry is particularly useful in all subdomains of communications where planar or spatial components are present: access networks, local loop, multicast trees, distributed games, hierarchical network architectures, in addition to all the wireless network problems listed above. TREC's favorite tools within this framework are Voronoi tessellations, coverage processes, random spatial trees and percolation. See http://www.di.ens.fr/~trec/sg/.

4. Application Domains

4.1. Application Domains

Depending on the classes of communication networks, we focus on different issues:

- Concerning the Internet, we concentrate on Internet probing and on the design of Internet overlay networks;
- Concerning operator networks, we work on the control and the optimization of both wireless cellular networks and wireline access networks;
- Concerning self-organized networks, we focus on the design of MAC and routing protocols and on the evaluation of the capacity.

We interact on these questions with the following industrial partners: Thomson (self organized networks), Alcatel (wireline access), France Télécom (wireless cellular networks) and Sprint (Internet probing and wireless access).

5. Software

5.1. SERT

Keywords: *admission control*, *blocking*, *capacity*, *cdma*, *outage*.

Participants: François Baccelli, Bartek Błaszczyszyn, Mohamed Karray [FT R&D].

A software called SERT (Spatial Erlang for Real Time services) was designed by M. Karray for the evaluation of various properties of large cdma networks and in particular the probability that calls are blocked due to the unfeasibility of the power control inherent to cdma. This tool is based on the research conducted with FT R&D described in Section 6.2.1 and in particular on the results of [43], [32] and patent pendings [44], [42], [41]. This software is now part of the dimensioning tools used by Orange for its UMTS network.

6. New Results

6.1. Analysis and Optimization of Flow-Control Protocols

Keywords: *AQM*, *IP networks*, *TCP*, *additive increase multiplicative*, *bit error*, *congestion prevention/control*, *decrease algorithm*, *feedback control*, *flow model*, *hybrid system*, *multicast*, *packet error*, *simulation*, *stability*, *synchronization*, *transmission error*.

Participants: François Baccelli, Augustin Chaintreau, Giovanna Carofiglio, Rene Cruz [University of California, San Diego], Serguei Foss [Heriot-Watt University, Edinburgh, UK], Anne-Marie Kermarrec [INRIA IRISA], Ki-Beak Kim [SAMSUNG], Fabien Mattieu [FT R&D], David McDonald [University of Ottawa, Canada], Antonio Nucci [NARUS], Marta Piancino, Julien Reynier, Danny De Vleeschauwer [ALCATEL NSG].

Operators require a methodology for analysing Internet traffic and control protocols to do resource planning (buffer capacities and bandwidth) capable of handling every possible mix of traffic (voice, video and data) with predefined end to end QoS, as well as overlay networks gathering large collections of interacting users and flows. Several research directions are pursued, ranging from the analysis of transport protocols on a single link to that of large overlay multicast or peer-to-peer networks.

6.1.1. Dynamics of TCP Flows

6.1.1.1. Dynamics of TCP flows in the AQM case.

This year, we started studying the case of long lived flows controlled by *scalable TCP*, a new protocol meant to handle very high speed connections. In [38], we extended the Mellin transform approach to this case and derived the distribution of the throughput.

The case of HTTP flows was studied in [19]. In this paper, we analyzed the average rate attained by a non persistent TCP source which alternates between idle periods and download periods subject to a fixed packet loss probability, when taking the slow start phase into account. Several distributions for the file sizes and idle times are considered including heavy tailed distributions. Using fixed point methods, these formulas can be applied to predict bandwidth sharing among competing HTTP flows subject to Active Queue Management.

6.1.1.2. Dynamics of TCP flows on wireless channels.

In [11] (joint work with R. Cruz and A. Nucci), we considered the case of a single TCP session traversing a wireless channel, with a constant signal to noise ratio (SINR) at the receiver. We considered the problem of determining the optimal transmission energy per bit, to maximize TCP throughput. Specifically, in the case where direct sequence spread spectrum modulation is used over a fixed bandwidth channel, we found the optimal processing gain m that maximizes TCP throughput. In the case where there is a high signal to noise ratio, we considered the scenario where adaptive modulation is used over a fixed bandwidth channel, and found the optimal symbol alphabet size M to maximize TCP throughput. When block codes are applied to each packet for forward error correction, we considered the joint optimization of the coding rate to maximize TCP throughput. In order to carry out the analysis, we obtained a TCP throughput formula in terms of the packet transmission error probability p and the transmission capacity C, which is of independent interest. In our TCP model, the window size is cut in half for each packet transmission loss, and also cut in half whenever the window size exceeds the transmission capacity C. This formula is then used to characterize the optimal processing gain or the optimal symbol alphabet size as the solution of a simple fixed point equation that depends on the wireless channel parameters and the parameters of the TCP connection.

6.1.1.3. Analysis of transport equations arising in the context of TCP Dynamics.

A general solution for the class of transport equations that arise within the context of both persistent and non persistent TCP flows was derived in [46], within the framework of a collaboration with K.B. Kim. This class contains two cases of loss point process models: the rate-independent Poisson case where the packet loss rate is independent of the throughput of the flow and the rate-dependent case where the point process of losses has an intensity which is a function of the instantaneous rate. In [46], we also give a direct proof of the fact that there is a unique density solving the associated differential equation and we provide a closed form expression for this density and for its mean value. The use of this approach for the anaysis of HTTP flows is considered in [19].

A survey on the applications of this class of transport equations to cross-layer optimization was presented at CISS in March [20].

6.1.1.4. Interaction of TCP Flows

6.1.1.4.1. Mean field models for interacting HTTP flows.

In [10], we discussed the mean field limit of a model for multiple HTTP sources multiplexed through a drop-tail router. This work is the outcome of a collaboration with D. De Vleeschauwer. The HTTP traffic, that is responsible for a large portion of the data transported today on communications network, is the result of the interplay between two mechanisms: instantaneous bandwidth sharing implemented by TCP, and dynamic properties of the traffic demand of each source, which alternates between requests of documents with varying sizes and period of inactivity. We analyzed the interplay between these two mechanisms using the hybrid Additive Increase Multiplicative Decrease (AIMD) model. Under memory-less assumptions on document size and think time, we can identify and analyze two possible steady state regimes for the mean field limit : a congestion-free steady state, where traffic is interactionless, and a periodic congestion steady state, where throughput is regulated by packet losses.

For certain parameter settings, we observed numerically that the system may reach one of these two regimes or the other depending only on the initial phasing of flows. The fact that a congestion steady state could be reached in cases where an interactionless regime is also possible may be seen as an analogue of turbulence.

6.1.1.4.2. Mathematics of mean field.

If N stochastic dynamical systems are coupled together through the use of a common resource one may describe the entire system via a histogram of all N states. In the mean field limit as $N \to \infty$ this histogram tends to a deterministic density. The publication [16] provides a new approach to this mean field convergence problem and tackles the mathematical parts of mean field convergence. This approach which first allowed us to analyse RED is now being extended Drop Tail through one router. Recently this methodology was extended to a wide class of problems including HTTP on/off sources modeled by the model in [10]. This extension as well as the mathematics of the mean field are parts of the PhD [7].

6.1.1.5. Overlay Networks

6.1.1.5.1. Interaction of TCP connections in overlay networks.

The scalability result found for the one-to-many TCP Overlay was extended to a class of dynamical discrete event systems, described by a system of Uniform Recurrence Equations (UREs). This class includes distributed protocols deployed on a large population of agents. We established that the speed of directional last-passage percolation is positive, if tasks completion times admit a finite moment of a certain order, and under simple organization condition. This condition is based on simple scalar products and it was shown to be necessary for a system of dimension $d = 2$. We extended this scalability result to a system organized over a general regular graph, under a more restrictive moment condition. The properties of a stationary regime for some of these infinite discrete event systems were analyzed using hydrodynamic limits.

These results are included in the thesis [6].

6.1.1.5.2. Split TCP.

TCP was mainly developed for wired reliable links, where packet losses occur mostly because of congestion. In wireless networks, performance problems arise as TCP often over-reacts to losses due to radio transmission errors. The split-connection approach is an overlay structure that has has been adopted to cope with this problem. In Split TCP, each TCP connection is split into two halves in order to achieve higher throughput. In the model that we developed with S. Foss we considered two long-lived TCP-Reno flows traversing two links with different medium characteristics in cascade. A buffer at the end of the first link will prevent the loss of packets that cannot be immediately forwarded on the second link by storing them temporarily. The target of our study is the characterization of the TCP throughput on both links as well as the buffer occupancy. We gave a representation of the system in terms of “piecewise-deterministic Markov process”, by referring the theory of PDPs developed by M.H.A. Davis in the ’80s. A PDP is a mixture of deterministic motion and random jumps associated to various configuration of the system. We proved stability by exploiting some sample pathwise continuity and monotonicity properties. We also developed an event-driven simulator in order to perform statistical tests devoted to verify the finiteness/infiniteness of certain moments as suggested by the analysis.

6.1.1.5.3. A filesharing model for P2P networks.

P2P networks provide better scalability for the filesharing applications they underlie. Unlike traditional server-based approach such as FTP, maintaining a constant QoS with a fixed number of servers seems feasible, whatever the number of peers involved. However, a P2P filesharing network sometimes happens to saturate, notably in a semi-P2P filesharing architecture or during flashcrowd phase, and scalability may fail. Even "smart" networks can encounter situations where the whole file but one piece is downloaded, which we call starvation. In [27], we suggested in collaboration with F. Mattieu a simple and versatile filesharing model. It applies to all pieces-oriented filesharing protocols used in softwares such as MlDonkey or BitTorrent. Simulations of this model show that starvation may occur even during flashcrowds. We propose a theoretical explanation for the so-called starvation phenomenon.

6.1.1.5.4. Load balancing in P2P networks while maintaining locality of contents.

With Anne-Marie Kermarrec, we showed in [37] that the problem of ranges queries in peer-to-peer networks can be solved using locality in the content distribution while maintaining the load balance. We found and showed some similarities between this problem and the quantization problem, studied mainly in the 80s. We proposed a new fully distributed algorithm allowing to allocate contents to the nodes of the network, with respect to any given distance on the contents, and while preserving an equal load on the nodes. We studied its performance through simulations and on real-traces, and found promising results.

6.2. Design and Performance Analysis of Wireless Networks

Keywords: *Boolean model*, *CDMA/UMTS*, *CSMA*, *Hiperlan*, *IEEE 802.11*, *MAC protocols*, *TCP*, *Wireless LANs*, *ad hoc networks*, *admission and congestion control*, *capacity*, *coverage*, *exponential back-off protocols*, *flow-level performance*, *mean field analysis*, *mesh networks*, *point processes*, *shot-noise*, *signal to interference ratio*, *spatial modeling*, *stability*, *stochastic geometry*, *transport capacity*, *voice over IP*.

Participants: François Baccelli, Nick Bambos [Stanford University], Bartek Błaszczyszyn, Thomas Bonald, Augustin Chaintreau [THOMSON], Carri Chan [Stanford University], Charles Bordenave, Sem Borst [LUCENT], Prasanna Chaporkar, Christophe Diot [THOMSON], Serguei Foss [Heriot-Watt University, Edinburgh, UK], Nidhi Hegde [FT R&D], Bruno Kauffmann, Vivek Mhatre [THOMSON], Paul Mühlethaler [INRIA Hipercom], David McDonald [University of Ottawa, Canada], Dina Papagiannaki [INTEL], Alexandre Proutière, Božidar Radunović, Vsevolod Shneer [Heriot-Watt University, Edinburgh, UK], Minh Anh Tran.

This axis concerns the analysis and the design of wireless access communication networks, in particular cellular networks, wireless LANs, MANETs, sensor networks etc. We are interested both in macroscopic models, which are particularly important for economic planning and in models allowing the definition and the optimization of protocols. Our approach combines several tools, queueing theory, point processes, stochastic geometry, random graphs, mean field techniques.

6.2.1. Load Control in Large Cellular Networks

6.2.1.1. Admission control.

In a series of previous papers co-authored by Mohamed Karray, most of which were published in IEEE Infocom, we developed some scalable load control schemes for large cellular networks with power control. These schemes are decentralized, in that they can be implemented in such a way that each base station only has to consider the load brought by its own users. Moreover, they allow one to control both elastic (data) and a CBR (voice) traffic: CBR traffic has a predefined bit-rate, and has to be regulated by an appropriate admission policy. Our approach applies to large, multi-cell networks; it is based on the sub-stochasticity condition imposed on the relative path-loss matrix introduced in [69]. When the spectral radius of this matrix is less than one, the global feasibility of the power allocation is guaranteed. In [43], using the sub-stochasticity condition, we established some extension of the classical Erlang's formula for blocking rates in cellular networks with fixed traffic. Our spatial Erlang formula is used by Orange; it was implemented in the SERT dimensioning tools (cf. Section 5.1).

6.2.1.2. Macrodiversity.

The results described above are derived under the assumption that each user is served by at most one base station. It is important to analyze networks where the base stations are jointly encoding and decoding signals. This kind of cooperation between base stations is called macrodiversity. On the downlink, mobiles are receiving a signal from several antennas and on the uplink, mobiles are sending a signal which is received by several antennas. The gain obtained with macrodiversity is an open issue and no admission control protocol has been proposed for these networks. We have derived some interesting counter intuitive results on macrodiversity. In particular, we have proved that the number of mobiles receiving a signal from more than two different antennas is bounded above by the number of antennas. We can prove that as the number of users grows large, the load of the network is asymptotically equivalent to the number of users times an explicit coefficient which depends on the positions of the base stations. Moreover, there exists a classical cellular network whose load is asymptotically equivalent to the load in the network in macrodiversity: macrodiversity on the downlink does not drastically improve the feasibility of the power allocation problem. However, on the uplink, macrodiversity has a much deeper impact on the network. We have extended the results of Hanly [57] to infinite networks and proved that if macrodiversity is enforced the feasibility condition depends only on the mean number of users per base station and the average bit rate required by users. In complete opposition with what happens on the downlink, the geometry of the network does not play any role. These results have been published in [13].

6.2.2. Cellular Data Networks

Unlike voice calls that are characterized by their duration, data flows are characterized by their size (in bits). The corresponding traffic intensity, defined as the product of the flow arrival rate by the mean flow size (in bits/s), may well exceed the cell capacity in the sense that the number of data flows increases continuously. Thus one distinguishes two milestones of the analytical evaluation of the performance of these networks: identification of its *stability region*; i.e., the maximum traffic intensity such that the system remains stable, and the evaluation of the *steady state characteristics*; e.g., the mean throughput.

6.2.2.1. Stability of data flows.

The notion of *cell capacity* is defined in [48] as the maximum traffic intensity such that the system remains stable. We applied this notion to various technologies including TDMA, CDMA and OFDM, and compared the results to the maximum capacity given by the information theory.

In [14] we are interested in the capacity of large networks, and more precisely in the *maximum number of bits per unit of surface and unit of time* that the network can handle without saturation. Inspired by previously developed scalable load control schemes and the analysis of macrodiversity (see Section 6.2.1) we have established a general framework for the stability analysis of such cellular data networks.

6.2.2.2. Performance evaluation of scalable congestion control schemes.

In a joint work [32] with Mohamed Karray, we systematically evaluate the performance of the congestion control policies derived from the load control schemes described in Section 6.2.1. We consider the bit-rate configurations identified by these schemes as *feasible sets for some classical, maximal fair resource allocation policies*, and study their performance in the long-term evolution of the system. Specifically, we assume Markovian arrivals, departures and mobility of customers, which transmit some given data-volumes, as well as some temporal channel variability (fading), and study the *mean throughput* i.e., the mean bit-rates that the policies offer in different parts of a given cell. Explicit formulas are obtained in the case of *proportional fair policies*, which may or may-not take advantage of the fading, for *null* or *infinitely rapid customer mobility*. This approach applies also to a channel shared by the elastic and a fixed traffic, with predefined customer bit-rates, regulated by the respective admission policy.

6.2.2.3. Combined inter-cell scheduling and cell selection.

In [47] (joint work with S. Borst) and [53] (joint work with N. Hegde) we examined the potential capacity gains in wireless data networks such as UMTS/HSDPA and CDMA 1xEV-DO from cell coordination which combines inter-cell scheduling and optimal cell selection. The inter-cell scheduling involves coordinating the activity phases of interfering base stations so as to avoid inter-cell interference and boost the transmission rates. The cell selection aims at improving the performance by assigning users to base stations based on load and other relevant considerations in addition to signal strength conditions. We consider a dynamic setting where users come and go over time as governed by the arrival and completion of random finite-size data transfers, and evaluate the capacity gains in terms of the maximum sustainable network throughput for a given spatial traffic pattern. We demonstrate that the relative merits of inter-cell scheduling and cell selection strongly depend on the network topology. In sparse (noise-limited) networks, optimal cell selection achieves substantial capacity gains and equalizes the loads across the various cells, while inter-cell scheduling yields no improvement. In contrast, in dense (interference-limited) networks, both inter-cell scheduling and optimal cell selection produce significant capacity gains, but due to interference, optimal cell selection no longer equalizes the loads and may even lead to strong load imbalances across cells.

6.2.2.4. Impact of intra- and inter-cell mobility and fading on network capacity.

In [24] (joint work with N. Hegde), we analyzed networks with several interacting base stations, and specifically examine the capacity impact of intra- and inter-cell mobility. We considered a dynamic setting where users come and go over time as governed by random finite-size data transfers, and explicitly allow for users to roam around over the course of their service. We showed that mobility tends to increase the capacity, not only in case of globally optimal scheduling, but also when each of the base stations operates according to a fair sharing policy. The latter approach offers the advantages that it avoids complex centralized control, and grants each user a fair share of the resources, preventing the potential starvation that may occur under a globally optimal strategy. An important implication is that a simple, conservative capacity estimate is obtained by 'ignoring' mobility, and assuming that users remain stationary for the duration of their service. We further demonstrated that the capacity region for globally optimal scheduling is in general strictly larger than the stability region for a fair sharing discipline. However, if the users distribute themselves so as to maximize their individual throughputs, thus enabling some implicit coordination, then a fair sharing policy is in fact guaranteed to achieve stability whenever a globally optimal strategy is able to do so.

6.2.3. Cellular Data Networks with WLAN/WPAN Relays

In [36], we consider the downlink of a cellular network supporting data traffic. In addition to the direct traffic from the base-station, each user is equiped with the same type of 802.11-like WLAN or WPAN interface, used to relay packets to further users and hence to improve the performance of the overall network. We are interested in analyzing what are the design guidelines for such networks, and how much capacity improvement can be brought by the additional relay layer in comparison to cellular networks. We consider a realistic dynamic setting where users randomly initiate downloads and leave the system upon transfer completion. A first objective is to provide a scheduling/relay strategy that maximizes the network capacity, i.e., the traffic in bit/s/cell that the network can support. We find that, regardless of the spatial traffic distribution, when the cell approaches saturation (the number of active users is very large), the capacity-achieving strategy divides the cell into two areas: one closer to the base-station where the relay layer is always saturated and some nodes receive traffic through both direct and relay links, and the further one where the relay is never saturated and the direct traffic does not exist. We further show that it is approximately optimal to use fixed link lengths, and we derive this length. We give a simple algorithm to calculate the cell capacity. The obtained capacity is shown to be independent of the cell size (unlike in traditional cellular networks), and it is 20%-60% higher than already proposed relay architectures when the number of users is large. Finally we provide guidelines for future protocol design.

6.2.4. Mean Field Analysis of Random Multi-Access Protocols in Wireless LANs

Using mean field techniques, we presented in [50] a performance analysis of random back-off algorithms, such as the exponential back-off algorithm, in the case of a finite number of saturated sources. The analysis assumed that all links were interfering with each other. In [52], [51], we generalize the results to the case of networks with partial interaction, i.e., to the case where all links do not interfere with each other. To do so, we represent the system as a system of interacting particles with a rapidly varying environment, and develop the mean field analysis of such systems. The results allow us to derive explicit expressions of the throughput of the various links, and we are then able to exactly quantify the well-known problem of unfairness in case of hidden nodes.

6.2.5. Mesh Networks

Mesh networking is a way to route data, voice and instructions between nodes. Mesh networks differ from cellular networks in that the component parts can all connect to each other via multiple hops, and from mobile ad-hoc networks in that their nodes generally are not mobile.

6.2.5.1. Single channel mesh networks.

We consider wireless multihop data networks with random multi-access mechanisms at the MAC layer where the various links shared the same channel. The aim of [26] (joint work with N. Hegde) is to study the performance as perceived by users in a dynamic setting where data flows are generated randomly by users and cease upon completion. This task comprises two major difficulties: first, the behavior of random multi-access algorithms at slot-level in a multi-hop network is even more complex than in the case of a single hop hotspot. Second, in order to study user-level performance, one has to characterize the rate region of the system, defined by the set of rates at which the different active users can generate packets without inducing any instabilities in the network. Since links interact with each other through interference, characterizing the rate region is as difficult as studying the behavior of a set of interacting queues. In addition, the behavior of the congestion control algorithm must be taken into account since it impacts the set of active links and then interference. We propose a model, based on decoupling arguments, that circumvents both difficulties and allows the derivation of explicit expressions for the rate region. Finally, using these expressions we analyze the flow-level performance of the network.

6.2.5.2. Design of multi-channel mesh networks.

Mesh networking has recently been advocated as an efficient and low-cost approach for providing high speed access to the Internet. Before mesh networks are able to provide high speed access to the Internet, a number of challenges must be addressed including routing, channel and radio interface assignments, radio resource management, and MAC scheduling. Our aim in [58] (joint work with N. Hegde) is to provide guidelines on the design of optimal radio resource management and distributed MAC scheduling algorithms. To this aim, we develop a general analytical model to characterize the performance of such networks. This task comprises many major difficulties: analyzing the behavior of distributed MAC schedulers in multi-hop networks, accounting for the interaction of links through interference and quantifying the impact of underlying congestion control algorithms. We present a unified approach partially based on decoupling arguments to circumvent these difficulties. Specifically, we characterize the rate region of the network, which is the set of rates at which the various data flows can be simultaneously transmitted. Based on the derived results, we can propose a set of provably optimal design rules for mesh multi-channel networks. For example, we investigate how to optimally parameterize the coverage of the RTS/CTS signalling messages in IEE802.11-based networks.

6.2.5.3. Cross-layer design of mesh networks.

In [67], we present an overview of cross-layer designs of mesh networks, as proposed in the literature. As opposed to ad-hoc networks, mesh networks have infrequent topology changes, and can be seen as fixed multi-hop wireless networks. Their design gathers the usual challenges of building high speed networks, where efficient routing protocols and congestion control algorithms have to be developed, and the challenges of optimizing the use of the expensive and limited radio resources. The development and deployment of wireless mesh networks would be greatly facilitated by pursuing the traditional layered approach (OSI layers), but this must not be at the expense of compromising an efficient utilization of the radio resources. Layers have then to be designed jointly and interact more with each other, in other words cross-layer design is needed. We first define what cross-layer design means, and give two different categorizations of existing cross-layer designs. We then introduce a new system building block structure that better capture different aspects of wireless design than the existing OSI structure. Finally, we illustrate different concepts on several existing cross-layer design examples.

6.2.5.4. Self-organizing of 802.11 access networks.

The popularity of IEEE 802.11 WLANs has led to today's dense deployments in urban areas. Such high density leads to sub-optimal performance unless wireless devices interfering in these networks learn how to optimally use and share the spectrum.

We proposed a set of distributed algorithms that allow (i) multiple interfering 802.11 Access Points to select their operating frequency in order to minimize interferences, and (ii) users to choose the Access Point they attach to, in order to get their fair share of the whole network bandwidth. Typical functions (choosing a channel to operate on, choosing an access point to associate with) were shown to be well-addressed in a common optimization framework based on Gibbs' sampler via the minimization of a potential energy function.

This scheme does not require explicit coordination among the wireless devices. For a fixed traffic demand, limited by wireless access, it was shown to achieve a fairness criterion identified in the past as the minimal potential delay [64]. We established the mathematical properties of the proposed algorithms and studied their performance using analytical, event-driven simulations. We discussed implementation requirements and showed that significant benefits can be gained even within incremental deployments and in the presence of non-cooperating wireless clients. We investigated several possibilities for real conditions evaluation.

In addition to the INRIA technical report [60], two papers, one on self-association and the other on power control in such mesh networks will be presented at IEEE INFOCOM 2007. These papers are the outcome of a collaboration with researchers at INTEL (D. Papagiannaki) and THOMSON (C. Diot, A. Chaintreau and V. Mhatre).

6.2.6. Mobile ad Hoc Networks

A mobile ad-hoc network (MANET) is made of mobile nodes which are at the same time terminals and routers, connected by wireless links, the union of which forms an arbitrary topology. The nodes are free to move randomly and organize themselves arbitrarily. Important issues in such a scenario are connectivity, medium access (MAC), routing and stability.

6.2.6.1. MAC optimization.

In [9], we have shown with Paul Mühlethaler how MAC protocols can be optimized for maximizing the network total transport capacity. We defined an Aloha type access control mechanism for large mobile, multihop, wireless networks, where it is important to find a compromise between the spatial density of communications and the range of each transmission. More precisely, we optimize the product of the number of simultaneously successful transmissions per unit of space (spatial reuse) by the average range of each transmission. The optimization is obtained via an averaging over all Poisson configurations for the location of interfering mobiles in a model where an exact evaluation of signal over noise ratio is used. The main mathematical tools stem from stochastic geometry and are spatial versions of the so called additive and max shot-noise processes. The resulting MAC protocol can be implemented in a decentralized way provided some local geographic informations are available to the mobiles. This MAC protocol shows very interesting properties. In particular, to the best of the authors knowledge, it is the first protocol to reach the Gupta and Kumar bound that does not require prior knowledge of the node density.

6.2.6.2. Opportunistic routing in MANET's.

In an ongoing work, also with Paul Mühlethaler, we focus on the analysis of routing protocols in multi-hop mobile wireless networks. In particular, we investigate the potential gains of opportunistic routing strategies which take advantage of both time and space diversity compared to classical routing strategies, where packets are routed on a pre-defined route usually obtained by a shortest path routing protocol. In the opportunistic routing scheme we consider, the relay is selected among the nodes having captured the packet transmission (if any) as the node which maximizes the progress of the packet towards the destination. In such a scheme, opportunism consists in taking advantage at each hop of the local pattern of transmission, where locality is understood in both its time and space sense. In our study we use a spatial version of Aloha for the MAC layer, which has been shown to scale well in multi-hop networks and a well established definition for the capture of packets based on the Signal over Interference and Noise Ratio (SINR) model. Our simulation study shows that such an opportunistic scheme very significantly outperforms classical routing schemes. It also shows how to optimally tune the MAC parameters so as to minimize the average number of hops from origin to destination everywhere in the network. This optimization is shown by simulation to be independent of the network density, a property that we back by a mathematical proof based on a scale invariance argument. We submitted our results to a conference organized in 2007.

6.2.6.3. *Stability of a random MACs with spatial interactions.*

The stability of decentralized access protocols is an important and difficult problem. In collaboration with Serguei Foss and Vsevolod Shneer we analyze the stability of an Aloha-type access protocol with a simplified form of spatial interaction [31]. To the best of our knowledge, no rigorous results were known in this field. At each time slot, an incoming flow of user arrives in the system and each user in the system tries to emit with a probability which is the inverse of the number of users in interaction with him (including himself). If a user is the only emitting user in its contention neighborhood, he/she leaves the system. If all users are jointly interacting, the stability condition for this system is well-known: the maximal arrival intensity is e^{-1}. Under appropriate technical assumptions, we have proved that the maximal arrival intensity is αe^{-1} where $\alpha \in (0,1]$ and $\alpha\lambda$ is the mean arrival intensity of users in interaction with a given user. This work paves the way to completely new results in this field.

6.2.6.4. *Power control for multihop routing.*

In a joint work [17] with N. Bambos and C. Chan we studied optimal power allocation strategies within the context of multihop routing. We addressed optimization issues associated with transmission schedules, links densities, etc. that are pertinent to performance of such structure in terms of throughput and the power/delay tradeoff. We introduced wireless link routing structures called ‘bracelets’ and we showed that linear (straight) link arrays are optimal for constant exogenous interference fields. We also addressed the problem of optimal large-scale routing in extraneous interference fields that vary in space.

6.2.7. Sensor Networks

In [33], we propose and analyze a probabilistic model of packet reception in the steady state regime of a non-slotted wireless communication channel as used in certain classes of transmit-only sensor networks. This can be viewed as an extension of the classical M/D/1/0 Erlang loss model where the *interference* created by different packet emissions is introduced by means of the shot-noise process. More precisely, we assume that a given packet is admitted by the receiver if this latter is idle at the packet arrival epoch and successfully received if, in addition, its signal-to-interference-and-noise ratio averaged over the reception period is large enough. As the main results we prove an analog of the Erlang formula for the fraction of the packets that are successfully received.

6.2.8. Distributed Scheduling in Wireless Networks

In [25] we address the question of attaining stability and fairness guarantees through distributed scheduling in wireless networks. We consider a simple, local information based, distributed scheduling policy called *maximal scheduling*. We prove that maximal scheduling attains a guaranteed fraction of the maximum stability region. The guaranteed fraction depends on the interference constraints due to underlying physical and MAC layer protocols. We obtain the stability guarantees for general interference constraints in the wireless networks. We also design a fully distributed algorithm that combines a token generation scheme with maximal scheduling policy so as to attain max-min fair rates within the feasible region of maximal scheduling.

6.2.9. Throughput Optimization in Loss-tolerant Wireless Networks

With advances in coding theory, many techniques have emerged that allow the recovery of the lost information efficiently. Examples of the techniques that require only some fraction of the packets to be received correctly for error-free construction of the complete message include digital fountain and network coding. Moreover, real-time applications can tolerate some loss without much degradation of the quality perceived by the end user. The loss-tolerance can be used to enhance the stability region of the system and also to simplify certain network protocols. In this work in progress, P. Chaporkar and A. Proutière characterize the stability (bounded mean queue length) of such systems and obtain policies that maximize the system throughput (the total number of packets received correctly at the receivers per unit time) while stabilizing the system.

6.3. Network Dynamics

Keywords: *Lyapounov exponent*, *Queueing network*, *Veraverbeke's theorem*, *estimator*, *insensitivity*, *inversion formula*, *large deviation*, *max-plus algebra*, *monotone-separable networks*, *probing*, *product-form networks*, *rare event*, *sub-additivity*, *sub-exponential distribution*.

Participants: François Baccelli, Jean Bolot [SPRINT ATL], Thomas Bonald, Ton Dieker [CWI], Sridhar Machiraju [University of California, Berkeley], David McDonald [University of Ottawa, Canada], Bruno Kauffmann, Marc Lelarge, Alexandre Proutière, Darryl Veitch [University of Melbourne, Australia].

6.3.1. Queueing Analysis of Data Networks

6.3.1.1. Data networks with convex rate regions.

In [12] and in [49] we compare the performance of three usual allocations, namely max-min fairness, proportional fairness and balanced fairness, in a communication network whose resources are shared by a random number of data flows. The model consists of a network of processor-sharing queues. The vector of service rates, which is constrained by some compact, convex capacity set representing the network resources, is a function of the number of customers in each queue. This function determines the way network resources are allocated. We show that this model is representative of a rich class of wired and wireless networks. We give in this general framework the stability condition of max-min fairness, proportional fairness and balanced fairness and compare their performance on a number of toy networks.

6.3.1.2. Flow-level stability of utility-based allocations for networks with arbitrary and time-varying rate region.

In [22], we investigate the stability of utility-maximizing allocations in networks with arbitrary rate regions, not necessarily convex, and in the case of two flow classes. We consider a dynamic setting where users randomly generate data flows according to some exogenous traffic processes. Network stability is then defined as the ergodicity of the process describing the number of active flows. When the rate region is convex, the stability region is known to coincide with the rate region, independently of the considered utility function. We show that for non-convex rate regions, the choice of the utility function is crucial to ensure maximum stability. The results are illustrated on the simple case of a wireless network consisting of two interacting base stations.

In a joint work [59] with colleagues at Princeton we extend the results of the previous paper, and characterize flow-level stochastic stability for networks with non-convex or time-varying rate regions under resource allocation based on utility maximization and for an arbitrary number of flow classes. Similar to prior works on flow-level stability, we consider exogenous data arrivals with finite durations. However, to model many realistic situations, the rate region which constrains the feasibility of resource allocation, may be either non-convex or time-varying. When the rate region is fixed but non-convex, we derive a sufficient and a necessary condition for stability, which coincide when the set of allocated rate vectors has continuous contours. When the rate region is time-varying according to some stationary, ergodic process, we prove the precise stability region. In both cases, the size of stability region depends on the resource allocation policy, in particular, on the fairness parameter α in α-fair utility maximization. This is in sharp contrast to the vast, existing literature on stability under fixed and convex rate regions, where stability region coincides with rate region for many utility-based resource allocation schemes. We further investigate the tradeoff between fairness and stability when rate region is non-convex or time-varying, and analytically characterize the tradeoff for two-class networks. Numerical examples on both wired and wireless networks are provided to illustrate the new stability regions and tradeoffs proved in the paper.

6.3.2. Insensitivity Property of Queueing Networks

In modern computer-science and telecommunication networks, it is advisable to share the resources so that, as for the telephone networks, the performance of these systems does not depend on the fine characteristics of the traffic generated by users. Thus for the data networks, one could identify the allowance of bandwidth ensuring that the average time of transfer of a queue depends only on the intensity of traffic and not on the distribution of the size of queues. This result uses a class of networks of processor-sharing queues for which the property of insensitivity is equivalent to a property of balance known since works of Kelly and Whittle.

We want to identify "the" class of insensitive queueing networks, i.e. to extend the preceding result with disciplines of service more general than processor sharing. A first result indeed shows that a "symmetric" queueing network satisfying the property of balance is insensitive. A more general result shows that this network remains insensitive even if random permutations are allowed at each event, and even if random permutations occur at the times of an independent Poisson process. It remains to show the reciprocal one, i.e. to determine if this class constitutes the set of insensitive queueing networks. The results were presented at the conferences MCQT 06 (http://www.mat.ucm.es/~mcqt/confe06/conf06.html) and “Journées MAS de la SMAI, Modèles Spatiaux” (http://math.univ-lille1.fr/~mas2006/).

6.3.3. Throughput Performance in Networks with Linear Capacity Constraints

In [21] we consider a network whose resources are shared by a dynamic number of data flows according to balanced fairness. We give explicit bounds on the mean throughput that results from this stochastic resource sharing when the capacity constraints are linear. The results apply to a number of wireline and wireless networks.

6.3.4. Rare Events in Stochastic Networks

6.3.4.1. Tail asymptotics for monotone-separable networks.

A network belongs to the monotone separable class if its state variables are homogeneous and monotone functions of the epochs of the arrival process. This framework contains several classical queueing network models, including generalized Jackson networks, max-plus networks, polling systems, multiserver queues, and various classes of stochastic Petri nets. We use comparison relationships between networks of this class with i.i.d. driving sequences and the $GI/GI/1/1$ queue to obtain the tail asymptotics of the stationary maximal dater under light-tailed assumptions for service times [35]. The exponential rate of decay is given as a function of a logarithmic moment generating function. We exemplify an explicit computation of this rate for the case of queues in tandem under various stochastic assumptions.

6.3.4.2. Asymptotics of subexponential max-plus network and packet reordering.

In a paper [15] with Ton Dieker we extended previous results obtained with Serguei Foss in [45]. We studied the stationary solution to a (max, plus)-linear recursion. Under subexponentiality assumptions on the input to the recursion, we obtained the tail asymptotics of certain (max, plus)-linear functionals of this solution. In the event graph setting, two special cases of our results are of particular interest and have already been investigated in the literature. Firstly, the functional may correspond to the end-to-end response time of the event graph. Secondly, for two queues in tandem, the functional may correspond to the sojourn time in the second queue. Our results allow for more general networks; we illustrated this by studying the asymptotics of the resequencing delay due to multi-path routing.

Due to random delays over different paths in a system, the packets or updates may arrive at the receiver in a different order than their chronological order. In such a case, a resequencing buffer at the receiver has to store disordered packets temporarily. In [62], we analyze both the waiting time of a packet in the resequencing buffer and the size of this resequencing queue. We derive the exact asymptotics for the large deviation of these quantities under heavy-tailed assumptions. In contrast with results obtained for light-tailed distributions, we show that there exists several “typical paths” that lead to the large deviation. We derive explicitly these different “typical paths” and give heuristic rules for an optimal balancing.

6.3.4.3. Sample path large deviations for queueing networks with Bernoulli routing.

The paper [34] is devoted to the problem of sample path large deviations for multidimensional queueing models with probabilistic routing that allows feedback. We derive a new version of the contraction principle where the continuous map is not well-defined on the whole space: we give conditions under which it allows to identify the rate function. We illustrate our technique by deriving a large deviation principle for a class of networks that contains the classical Jackson networks

6.3.5. Queueing Theory for Active Probing

6.3.5.1. Inversion problems.

Active probing began by measuring end-to-end path metrics, such as delay and loss, in a direct measurement process which did not require inference of internal network parameters. The field has since progressed to measuring network metrics, from link capacities to available bandwidth and cross traffic itself, which reach deeper and deeper into the network and require increasingly complex inversion methodologies. The paper [63] is an outcome of a collaboration with S. Machiraju, D. Veitch, and J. Bolot. In this paper, we proposed inversion formulas based on queueing theory allowing one to analyze the law of cross traffic in a router from the time series of the end-to-end delays experienced by probes. We also investigated the limitations of such inversion formulas. We used the resulting insight to design practical estimators for cross traffic, which we tested in simulation and validated by using router traces.

6.3.5.2. Estimation problems.

In active probing, PASTA is invoked to justify the sending of probe packets (or trains) at Poisson times in a variety of contexts. However, due to the diversity of aims and analysis techniques used in active probing, the benefits of Poisson based measurement, and the utility and role of PASTA, are unclear. With the same group of authors (S. Machiraju is now at SPRINT), and using a combination of rigorous results, examples and counter-examples, we have shown that PASTA is of very limited use in active probing. In particular, Poisson probes are not unique in their ability to sample without bias. Furthermore, PASTA ignores the issue of estimation variance, and the central need for an inversion phase to estimate the quantity of interest based on what is directly observable. These issues are addressed in [18] where we also give concrete examples of when Poisson probes should not be used, and explain why, and offer initial guidelines on suitable alternative sending processes.

6.3.5.3. Internet Tomography.

Active probing suffers presently of the “Bottleneck” limitation: all characteristics of the path after the bottleneck link are unreachable with current techniques. The botleneck link erases all the later effects. In a joint work with Darryl Veitch, we are currently investigating a new tomography technique, based on the measurements of end-to-end delays, which should allow one to have access to several hidden metrics such as the available bandwidth for every link on the path.

6.4. Point Processes, Stochastic Geometry and Random Graphs

Keywords: *ergodicity*, *loss system*, *random matrices*, *random trees*, *scaling exponent*.

Participants: David Aldous [University of California, Berkeley, USA], François Baccelli, Pierre Brémaud, Bartek Błaszczyszyn, Charles Bordenave, Marc Lelarge, Perla Sousi, Giovanni Luca Torrisi [CNR, Roma, Italy], Yogeshwaran Dhandapani [Indian Institute of Science].

This year our work within this framework is focused on percolation models, on spanning trees, both random and minimal ones, on spectral properties of random matrices associated with random graphs of the Euclidean space.

6.4.1. Percolation

Connectivity is probably the first issue that has to be addressed when considering large-scale MANETs. The mathematical analysis of this problem involves random graphs associated with various models typically driven by Poisson point processes on the plane. Percolation properties of these graphs (existence of a giant component) are interpreted as an indication that the connectivity of the ad hoc network scales well with the size. Probably the first percolation model explicitly proposed for wireless communication networks, was studied by Gilbert already in 1961 (see [56]). It is now considered as the classical continuum model in percolation theory and accepted in wireless communications as such, despite the fact that it ignores the interference effect that arises when many transmitters are active at the same time. Recently the use of shot-noise processes allowed us to study the impact of interferences on the connectivity of large-scale ad-hoc networks using percolation theory (see [54], [55]). An important observation is that, contrary to Gilbet’s model, connectivity is not always improved by densification.

The existing model assumes constant emitted powers and bi-directional connections. Current work in this domain (in TREC) concerns extensions to random (in particular controlled) powers and uni-directional communications.

6.4.2. Random Spanning Trees

We have defined and analyzed a new model in geometric probability: the radial spanning tree (RST). The RST is a spanning tree over a locally finite point set. It has a distinctive root taken as the origin and a simple local structure: the ancestor of a vertex is the closest point from the vertex which is closer than the vertex to the origin. When this point set is a Poisson point process on the plane we have performed a careful analysis of its main features. This work is the object of a forthcoming publication in the Annals of Applied Probability.

This work has been extended to the more general framework of the analysis of decentralized spanning trees over Poisson point processes. This type of structures appears naturally in routing issues in wireless networks and in peer to peer networks. This work on trees has led to a research report [30], a publication in the proceedings of Spaswin [23] and a submission. Such trees are also considered in the thesis [5].

6.4.3. Minimal Spanning Trees

Freshman calculus tells us how to find a minimum x_* of a smooth function $f(x)$: set the derivative $f'(x_*) = 0$ and check $f''(x_*) > 0$. The related series expansion tells us, for points x near to x_*, how the distance $\delta = |x - x_*|$ relates to the difference $\epsilon = f(x) - f(x_*)$ in f-values: ϵ scales as δ^2. This *scaling exponent* 2 persists for functions $f : \mathbb{R}^d \to \mathbb{R}$: if x_* is a local minimum and $\epsilon(\delta) := \min\{f(x) - f(x_*) : |x - x_*| = \delta\}$, then $\epsilon(\delta)$ scales as δ^2 for a generic smooth function f.

Combinatorial optimization, exemplified by the *traveling salesman problem* (TSP), is traditionally viewed as a quite distinct subject, with theoretical analysis focusing on the number of steps that algorithms require to find the optimal solution. To make a connection with calculus, compare an arbitrary tour $\mathbf{x}$ through n points with the optimal (minimum-length) tour $\mathbf{x}_*$, by considering the two quantities

$$\delta_n(\mathbf{x}) = \{\text{number of edges in x but not in x}_*\}/n$$
$$\epsilon_n(\mathbf{x}) = \{\text{length difference between x and x}_*\}/s(n)$$

where $s(n)$ is the length of the minimum length tour. Now define $\epsilon_n(\delta)$ to be the minimum value of $\epsilon_n(\mathbf{x})$ over all tours $\mathbf{x}$ for which $\delta_n(\mathbf{x}) \geq \delta$. Although the function $\epsilon_n(\delta)$ will depend on n and the problem instance, we anticipate that for typical instances drawn from a suitable probability model it will converge in the $n \to \infty$ limit to some deterministic function $\epsilon(\delta)$. The *universality* paradigm from statistical physics suggests there might be a scaling exponent α defined by

$$\epsilon(\delta) \sim \delta^\alpha \text{ as } \delta \to 0$$

and that the exponent should be robust under model details.

There is fairly strong evidence that for TSP the scaling exponent is 3. This is based on analytic methods in a *mean-field* model of interpoint distances (distances between pairs of points are random, independent for different pairs, thus ignoring geometric constraints) and on Monte-Carlo simulations for random points in 2, 3 and 4 dimensional space. The analytic results build upon a recent probabilistic reinterpretation of the work of Krauth and Mézard establishing the average length of mean-field TSP tours. But neither part of these TSP assertions is rigorous, and indeed rigorous proofs in d dimensions seem far out of reach of current methodology. In contrast, for the *minimum spanning tree* (MST) problem, a standard algorithmically easy problem, a simple heuristic argument strongly suggests that the scaling exponent is 2 for any reasonable probability model. The goal of the paper [28], in collaboration with D. Aldous is to work through the details of a rigorous proof.

6.4.4. Euclidean Random Matrices

Random matrices have a large field of applications in communication networks and they have been used successfully for example in information theory and network epidemics. We have started to investigate the potential applications of random matrices in geometric probability. Following the seminal work of [65], we have analyzed the spectral properties of Euclidean random matrices. We draw n points in a compact set and the entry (i,j) of such matrices is a function of the distance between points i and j. If this function is an indicator function, this matrix is the adjacency matrix of the geometric graph. In [29] we prove rigorously some of the results stated in [65] and we derive new formulas for the spectral radius of these matrices and for the empirical measure of their eigenvalues. In particular, we relate the spectrum of Euclidean random matrices to the Fourier transform of the function of the distance between two points.

This work is the first step of an ongoing research project. From the work of [61], [66], we may infer a relation between the critical percolation threshold and the limiting empirical measure of the eigenvalues of the Laplacian matrix of a graph. We are currently trying to extend the results [29] to a larger class which include the Laplacian matrix of a geometric graph. The aim is to obtain a new characterization of the percolation threshold based on spectral properties.

6.4.5. Functionals of Poisson Point Processes

With Giovanni Luca Torrisi we worked on the computation of the derivatives of functionals of Poisson point processes in $\mathbb{R}^d$. A paper has been submitted for publication in Advances in Applied Probability. We have derived Monte Carlo methods to estimate these derivatives. This work is motivated by the sensitivity analysis of well known structures in geometric probability such as the cluster containing the origin in continuum percolation in the subcritical regime or the typical Poisson Voronoi cell. In one dimension we have also applied our results to some stopping times in a Poisson shot-noise. The importance sampling technique allows, through a change of measure, to write this problem in terms of derivatives of functional of Poisson point process. Applications of this work include sensitivity analysis of ruin probability in insurance mathematics and tail probability of waiting time in a M/GI/1 queue.

In another work, we have computed the large deviation principle for the number of points of Poisson cluster process $\mathbb{R}^d$ in a large set. The rate function is explicitly computed and we have derived in particular new formulas for the void probability of a large set and for the number of points in a large set for a Hawkes process. This work has been submitted to Stochastic Models.

6.4.6. Shot-Noise Processes

Explicit performance evaluation of stochastic geometry models of wireless communication networks is almost entirely confined to scenarios with stationary (homogeneous) Poisson repartition of objects. Adopting homogeneous scenarios in communication models, however, is often too simplistic, since it ignores the spatial fluctuations of the traffic. Modeling of inhomogeneity is not an easy task; adequate and tractable non-homogeneous models are yet to be identified.

We considered Poisson-Poisson cluster processes in the context of the SINR coverage process developed in [40], as they still allow for many explicit formulas and at the same time offer much more flexibility in modeling than the class of homogeneous Poisson processes. This work was reported in [39].

Mathematical tractability often requires exponential distributions, which are also some kind of simplifying assumption (even if compatible with Rayleigh fading). We also considered phase-type emitted power distributions in the context of the SINR coverage process. This work was reported in [68].

7. Contracts and Grants with Industry

7.1. Research Grant of Thomson

Participants: François Baccelli, Bartek Błaszczyszyn, Bruno Kauffmann, Marc Lelarge.

The collaboration with the new Paris Lab of THOMSON has been developing very fast since its creation. The scientific ties with C. Diot, L. Massoulié and A. Chaintreau are quite strong and materialize into:

- joint seminars and reading groups (notably the new Paris-Networking series that we jointly initiated);
- joint research actions, particularly on routing in ESS mesh WiFi networks and on CDMA networks;
- a grant from Thomson which allows us to invite well known scientists in Communications (like e.g. V. Anantharam from Berkeley);
- various ongoing projects of joint proposals in national and European agencies.
- several joint papers published this year or to be published soon (including two Infocom 07 papers).

7.2. Research Contract with Alcatel Bell "Choking of UDP traffic”

Participant: François Baccelli.

We initiated a new project with the Network Strategy Group of Alcatel Antwerp in continuation of the "End to End" OSC that ended in 2005. The new research directions are pursued in collaboration with Danny de Vleeschauwer and Koen Laevens. They bear on the modeling of the interaction of a large collection of multimedia sources that join and leave and that share an access network. The main objective is the design of optimal choking policies for the transport of layer encoded video in access networks.

7.3. Collaboration with France Télécom

Participants: François Baccelli, Bartek Błaszczyszyn, Mohamed Karray [FT R&D].

The collaboration with France Télécom was structured in two parts:

- The PRIMO CRC (Partage de Ressources dans l’Internet et les réseaux MObiles). The CRC, which ended in August 2006 after two years of existence, was focused on teletraffic theory and aimed at extending this theory to the classes of communication networks that are used and designed by operators today. The research activity covered both wireline and wireless networks. The main mathematical tools to be investigated within this context are queueing theory, information theory and stochastic geometry.
- Our "Spontaneous Collaboration" with M. Karray on the coverage and capacity of the CDMA/UMTS networks. The current work primarily bears on macrodiversity in UMTS, multisectorial antennas in CDMA, distributed power and admission control for UMTS and associated QoS questions. Three patents were filed on these questions, one by INRIA and two jointly by INRIA and FT. The pertinence of our approach has already been recognized by Orange. This operator uses some of our methods in the program SERT (see Section 5.1) integrated to its dimensioning tools. This year again, the spontaneous collaboration with M. Karray lead to a new joint paper [32] accepted for publication at Infocom 07.

7.4. Sprint ATL Grant

Participants: François Baccelli, Marc Lelarge.

The interaction with the research lab of Sprint (Sprint ATL, in Burlingame, California) is made possible through a research grant. This interaction has been focused on two main topics:

- The design of active probing methods for the estimation of internal properties of core or access networks based on end-to-end measurements. In the paper [63] we proposed inversion formulas allowing one the analyze the law of cross traffic in a router from the end-to-end delay of probes. We also investigated the limitations of such inversion formulas. There are several continuations of this line of thoughts currently under investigation.
- Cross layer optimization in CDMA cellular networks. In the paper [11], we gave an explicit formula for the optimal processing gain of a TCP source on the downlink of a CDMA channel. The analysis can be extended to other cross layer optimization problems involving congestion control and physical layers like in particular within the context of adaptive modulation.

Other projects have been started on the architecture of heterogeneous wireless networks. This collaboration is quite fruitful. It lead to two papers this year (including a Sigcomm 06 paper).

8. Other Grants and Activities

8.1. Networks and International Working Groups

- The France-Stanford Center has accepted a joint project entitled "Analysis and Design of Next-Generation Wireless Networks" that we submitted jointly with Prof. N. Bambos of Stanford in 2006. This project will be funded in 2006-2007.
- TREC obtained in November 2006 the INRIA status of *Associated Lab* (équipe associée) for the group of Prof. Darryl Veitch of the University of Melbourne for developing our joint research action on active probing.
- TREC is a partner in the *European Network of Excellence (NoE)* called EuroNGI (2004–2006; http://eurongi.enst.fr/en_accueil.html) led by Groupement des Ecoles des Télécoms (GET). TREC was the coordinator of the INRIA participation to this NoE.

9. Dissemination

9.1. Animation of the Scientific Community

9.1.1. TREC's seminar

the following scientists gave talks in 2006:

- France
  - Defense of the PhD thesis of Augustin Chaintreau *ENS Paris*, "Processes of Interaction in Data Networks", January 16,
  - Romain Brette from *ENS Paris* talking on "Réseaux de neurones et probabilités", March 8,
  - Pascal Moyal (CEREMADE, Université Paris Dauphine) "Stationarity of pure delay systems and queues with impatient customers via stochastic recursions", May 5,
  - Charles Bordenave (ENS) "Navigation on a Poisson point process", May 5,
  - Glenn Merlet "Théorèmes limites pour des suites récurrentes stochastiques d'applications topicales", May 5,
  - Fabien Mathieu (France Télécom) "Dynamic Roommates: a Versatile Framework for P2P Networks", May 5,
  - Defense of the PhD thesis of Charles Bordenave, ENS Paris, "Analyse stochastique des réseaux spatiaux", July 4,
  - Defense of the PhD thesis of Julien Reynier, ENS Paris, "Modélisation mathématique de TCP à l'aide de méthodes de champ moyen", September 15,
  - Dao Thi Thu Ha from *LIAFA-Paris VII* talking on "Les files 0-automatiques", October 20,
  - Justin Salez from *ENS Paris* talking on "Convergence locale de graphes aléatoires et propagation de croyances en milieu cyclique", October 20,
  - Laurent Massoulié from *Thomson Research Paris,* talking on "Stability of decentralized control mechanisms: from congestion control to peer-to-peer broadcasting", November 3,

  - Eitan Altman from *INRIA Sophia Antipolis,* talking on "Potential Games in Wireless Networks", November 13.
- Europe
  - Frank Kelly from *Cambridge University, UK* talking on "Stability, routing and congestion control", January 16,
  - Serguei Foss from *Heriot-Watt University, Edinburgh, UK* talking "On the stability of a queueing system with uncountably branching fluid limits" and on "Stability of a network of multi-access broadcast channels with spatial interaction", March 16,
  - Artyom Sapozhnikov from *University College Cork, Ireland* talking on "Connectivity in subcritical continuum percolation", May 15,
  - Henri Koskinen from *Helsinki University of Technology, Finland* talking on "Geometric studies in wireless multihop networks", July 5,
  - Serguei Foss from *Heriot-Watt University, Edinburgh, UK* talking on "Lower bounds and equivalences for randomly stopped sume", November 29.
- America, Asia, Australia
  - Prasanna Chaporkar *University of Pennsylvania, Philadelphia, PA, USA / ENS - Paris* talking on "MAC Layer Multicast: Theory and approaches", January 4, 2006,
  - Nicholas Bambos from *EECS Stanford, USA* talking on "Power control for wireless networks, an overview and some new directions", February 2,
  - Yogeshwaran Dhandapani from *Indian Institute of Science, India,* talking on "Coverage Processes and Applications to Target Tracking in Sensor Networks", May 15,
  - Wojciech Szpankowski from *Purdue University, Indiana, USA* talking on "Analytic algorithmics, combinatorics, and information theory", June 2,
  - David McDonald from *University of Ottawa, Canada,* talking on "Large deviations of multitype queues", June 26,
  - Darryl Veith from *University of Melbourne, Australia* talking on "Generalizing Fractional Brownian Motion in discrete time: a surprising self-similarity", July 12,
  - Anatolii Puhalskii from *Colorado University, Denver and Institute for Problems in Information Transmission, Moscow,* talking on "Some Asymptotics for the Erdos-Renyi Random Graph", November 22.

9.1.2. Miscellaneous

- TREC animates the project-team seminar: http://www.di.ens.fr/~trec/trec-eng.html
- TREC is a founding member of and participates to Paris-Networking (http://www.paris-networking.org/), a virtual community of researchers in networking who work in or around Paris (or visit Paris).
- M. Lelarge animates the project-team reading group.
- B. Błaszczyszyn maintains a web-page on stochastic geometry for communications http://www.di.ens.fr/ trec/sg
- B. Błaszczyszynis a member of the organizing committee of the Scientific Colloquium of INRIA Rocquencourt *Le modéle et l'algorithme* (http://www-rocq.inria.fr/fr/actualites/modeleetalgorithme/).
- F. Baccelli collaborates with G. Giraudon on the follow up of the interactions between INRIA and FT R&D.

- P. Brémaud is a member of the editorial board of the following journals: *Journal of Applied Probability, Advances in Applied Probability, Journal of Applied Mathematics and Stochastic Analysis*;
- F. Baccelli is a member of the editorial board of the following journals: *QUESTA, Journal of Discrete Event Dynamical Systems, Mathematical Methods of Operations Research, Advances in Applied Probability*.

9.2. University Teaching

Télécom Paris Course on queueing theory and network performance evaluation by T. Bonald and A. Proutière (18H).

University of Pierre and Marie Curie, Paris 6

- Graduate Course on point processes, stochastic geometry and random graphs (program “Master de Sciences et Technologies”), by F. Baccelli, B. Blaszczyszyn and L. Massoulié (45h).
- "Travaux dirigés" on arithmetics by M.A. Tran (39h).

Ecole Normale Supérieure

- Course on Information Theory of P. Brémaud and C. Bordenave (36h).
- Undergraduate course (master level, MMFAI) of F. Baccelli, T. Bonald, A. Proutière, B. Radunović and M.A. Tran on Communication Networks (48H).
- Undergraduate course (master level) of F. Baccelli, P. Brémaud and M. Lelarge on applied probability (48h).

Politecnico di Torino Course on PDE’s for flow control by F. Baccelli (30h).

9.3. Invitations and Participation in Conferences

F. Baccelli

- Member of the thesis committee of A. Chaintreau (ENS and Corps des Télécoms, January 16), C. Bordenave (Ecole Polytechnique and Corps des Télécoms, July 4) and J. Reynier (ENS and Corps des Télécoms, September 15).
- Member of the program committee of the following conferences: Spaswin 06 (http://icawww1.epfl.ch/spaswin/), Infocom 06 (http://www.ieee-infocom.org/2006), Sigmetics/Performance 06 (http://www.cs.wm.edu/sigm06/), WiOpt 06 (http://www.wiopt.org/wiopt06/).
- Presentation at the following conferences:
  - Workshop on Information Theory and its Applications, La Jolla, USA, February 2006 (http://ita.ucsd.edu/events/1/workshops/showall/),
  - CISS, Princeton, March 2006 (http://conf.ee.princeton.edu/ciss/),
  - SPASWIN 2006, Boston, USA, April 2006 (http://icawww1.epfl.ch/spaswin/).
  - INFOCOM, Barcelona, Spain, April 2006 (http://www.ieee-infocom.org/2006),
  - Conference on Stochastic Networks, Urbana-Champaign, USA, June 2006 (http://www.ifp.uiuc.edu/~srikant/stochnet.htm),
  - 7th IEEE International Workshop on Signal Processing Advances for Wireless Communications (SPAWC 06), Cannes, France, July 2006; keynote lecture (http://spawc2006.eurecom.fr/),

  - * Sigcomm Conference, Pisa, Italy, September 2006 (http://www.acm.org/sigs/sigcomm/sigcomm2006/),
  - * Second International Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS 06), Pisa, Italy, October 2006 (http://www.valuetools.org/).
- Organization of a session on self organized networks at *Grand colloque STIC*, Lyon, France, November 2006 (http://www.rntl.org/colloqueTIC2006/index.html),
- Presentation at the following seminars:
  - * TCOM, Philadelphia, USA, March 2006,
  - * Académie des Sciences public session, Nice, France, May 2006.
- Series of lectures at the 28th Finnish Summer School on Probability Theory, Nagu, Finland, with a course on Stochastic Geometry and Wireless Network Modeling, June 2006 (http://www.abo.fi/fak/mnf/mate/nagu06/).

B. Błaszczyszyn

- Member of the thesis committee of Nathalie Mitton (Université Lyon 1)
- Reviewer of the thesis of Henri Koskinen, (Helsinki University of Technology),
- Member of the program committee of Infocom 07 (http://www.ieee-infocom.org/2007),
- Co-organizer of the session "Géométrie aléatoire et applications aux réseaux" during "Journées MAS de la SMAI, Modèles Spatiaux", *Polytechnique de Lille*, September 2006, (http://math.univ-lille1.fr/~mas2006/)
- Presentations at the following conferences:
  - * "The World a Jigsaw: Tessellations in the Sciences", University of Leiden and Lorentz Center, Netherlands, March 2006; invited talk (http://www.lc.leidenuniv.nl/lc/web/2006/169/info.php3?wsid=169),
  - * 9th Conference on Probability, Będlewo, Poland, May 2006 (http://www.impan.gov.pl/~prob2006/),
  - * "Journées MAS de la SMAI, Modèles Spatiaux", Polytechnique de Lille, France, September 2006 (http://math.univ-lille1.fr/~mas2006/),
  - * Workshop on "Applied Probability and Stochastic Geometry", University of Wroclaw, Poland, October 2006 (http://www.math.uni.wroc.pl/news_events/events.php?eventid=04102006workshop&eventnr=14).
- Presentation at the seminar "Groupe de Travail "Probabilités" ", Université Paris 5, December 2006 (http://www.math-info.univ-paris5.fr/~dhersin/GTProbaP5/GTProbaP5.html).

T. Bonald

- Member of the program committee of Sigmetrics/Performance 2006 (http://www.cs.wm.edu/sigm06/), RAWNET 2006 (http://www.rawnet.org/2006/index.html).
- Presentations at CISS, Princeton, March 2006 (http://conf.ee.princeton.edu/ciss/).

Ch. Bordenave

- Presentation at the following conferences:
  - * ALEA 2006, Marseille-Luminy, France, March 2006 (http://www-rocq.inria.fr/~robert/Conf/ALEA06/).
  - * SPASWIN 2006, Boston, USA, April 2006 (http://icawww1.epfl.ch/spaswin/).

    * Colloquium "Jeunes Probabilistes et Statisticiens", Aussois, France, April 2006,
    * Conference on "Limit Theorems in Probability Theory and Their Applications", Novosibirsk, Russia, August 2006 (http://math.nsc.ru/LBRT/v1/conf2006),
    * “Journées MAS de la SMAI, Modèles Spatiaux”, Polytechnique de Lille, France, September 2006 (http://math.univ-lille1.fr/~mas2006/).
  – Participation at WiOpt, Boston, USA, April, 2006 (http://www.wiopt.org/wiopt06/),
  – Presentation at the following seminars:
    * École Nationale Supérieure des Télécommunications, Paris, May, 2006 (http://www.tsi.enst.fr/~cappe/sta/eve.html).
    * École Normale Supérieure, Séminaire TREC, Paris, May, 2006 (http://www.di.ens.fr/~trec/sem-trec_fr2005-2006.html).

G. Carofiglio

  – Presentation at the conference ACM Sigmetrics/Performance MAMA Workshop, Saint-Malo, June, 2006. (http://www.cs.wm.edu/sigm06/MAMAindex.html),
  – Participation at EuroNGI Summerschool on Network Strategy, Design and Dimensioning, Laredo, Spain, September 2006 (http://www.tlmat.unican.es/eurongi/summerschool2006/).

A. Chaintreau

  – Received the prize for his PhD thesis [6] granted by the *Société des Personnels Enseignants et Chercheurs en Informatique de France* (SPECIF), it will be handled during the SPECIF congress in January 2007 (http://www.labri.fr/manifestation/specif2007/).
  – Presentation at the seminar École Normale Suérieure, Séminaire TREC, Paris, January, 2006 (http://www.di.ens.fr/~trec/sem-trec_fr2005-2006.html).

P. Chaporkar

- Presentation at the following seminars:
  – “Avant-Première Infocom” Paris Networking, April 2006 (http://www.paris-networking.org/),
  – Network modeling day in ENS, May 2006 (http://www.di.ens.fr/~trec/sem-trec_fr2005-2006.html),
  – Statistical Laboratory, University of Cambridge,
  – EECS Stanford University,
  – Heriot Watt University, Edinburgh,
  – University of California, Berkeley,
  – University of Massachusetts, Amherst.

A. Proutière

  – Co-chair of IEEE RAWNET (http://www.rawnet.org/2006/index.html), the second workshop on Resource Allocation in Wireless Networks, in conjunction with WiOpt 2006 (http://www.wiopt.org/wiopt06/), Boston, April 2006.
  – Member of the TPC of the following conferences: IEEE Infocom 2006-2007 (http://www.ieee-infocom.org/2006) (http://www.ieee-infocom.org/2007)
  – Presentation at the following conferences:
    * CISS, Princeton, March 2006 (http://conf.ee.princeton.edu/ciss/),
    * AINA, Vienna, April 2006; Key note speaker (http://www.takilab.k.dendai.ac.jp/conf/aina/2006/).

- Presentation at the following seminars:
  * Princeton, March, 2006,
  * Microsoft Research, Cambridge, June 2006,
  * Heriot-Watt University, Edinburgh, June 2006,
  * Bell Labs, August 2006,
  * UPenn, July 2006,
  * Sprint Labs, August 2006,
  * University of Ottawa, October 2006.

B. Radunović

- Presentation at the following seminars:
  * EPFL, Lausanne, October 2006,
  * Microsoft Research, Cambridge, UK, May 2006,
  * Intel Research, Cambridge, UK, June 2006.

J. Reynier

- Participations at the following conferences:
  * ICIW, French Caribbean, February 2006; work presented by Fabien Mathieu (http://www.iaria.org/conferences/ICIW06.html).
- Presentation at the following seminars:
  * Thomson Paris Research Lab, Boulogne, June 2006 (http://www.thomson.net/EN/Home/Technology/research_activities/paris_lab_overview.htm) peer to peer systems and marriage theory.
  * France Télécom R&D Issy, July, 2006: mean field model for RED.
  * Motorola Lab Saclay, August 2006: mean field model for RED.
  * Paris Networking, ENS Paris, September 2006; thesis defense (http://www.paris-networking.org/).

M. A. Tran

- Presentations at the following conferences:
  * Second Madrid Conference on Queueing Theory (MCQT 06), Madrid, Spain, July 2006 (http://www.mat.ucm.es/~mcqt/confe06/conf06.html),
  * "Journées MAS de la SMAI, Modèles Spatiaux", Polytechnique de Lille, France, September 2006 (http://math.univ-lille1.fr/~mas2006/).

10. Bibliography

Major publications by the team in recent years

[1] F. Baccelli, P. Brémaud. *Elements of Queueing Theory*, Série: Applications of Mathematics, second edition, Springer Verlag, 2002.

[2] F. Baccelli, P. Brémaud. *Modélisation et Simulation des Réseaux de Communication*, Ecole Polytechnique, 2002.

[3] P. BRÉMAUD. *Mathematical Principles of Signal Processing*, Springer-Verlag, 2002.

[4] P. BRÉMAUD. *Point Processes and Queues: Martingale Dynamics*, Springer-Verlag, 2005.

Year Publications

Doctoral dissertations and Habilitation theses

[5] C. BORDENAVE. *Stochastic Analysis of Spatial Networks*, Ph. D. Thesis, Ecole Polytechnique, July 2006.

[6] A. CHAINTREAU. *Processes of Interaction in Data Networks*, Ph. D. Thesis, Ecole Normale Supérieure and Université Paris 6, January 2006.

[7] J. REYNIER. *Modélisation et simulations de TCP par des méthodes de champ moyen*, Ph. D. Thesis, École polytechnique, September 2006.

Articles in refereed journals and book chapters

[8] F. BACCELLI. *Les réseaux de communication*, in "La Lettre de l'Académie", vol. 19, 2006.

[9] F. BACCELLI, B. BŁASZCZYSZYN, P. MÜHLETHALER. *An Aloha Protocol for Multihop Mobile Wireless Networks*, in "IEEE Transactions on Information Theory", vol. 52, n^{o} 2, 2006, p. 421–436.

[10] F. BACCELLI, A. CHAINTREAU, D. DE VLEESCHAUWER, D. MCDONALD. *HTTP Turbulence*, in "AMS Networks and Heterogeneous media (NHM)", vol. 1, 2006, p. 1–40.

[11] F. BACCELLI, R. CRUZ, A. NUCCI. *Wireless Channel Parameters Maximizing TCP Throughput*, in "IMA Volumes in Mathematics and its Applications", Volume on Wireless Communications, vol. 143, 2006.

[12] T. BONALD, L. MASSOULIÉ, A. PROUTIÈRE, J. VIRTAMO. *A queueing analysis of maxmin fairness, proportional fairness and balanced fairness*, in "Queueing systems and their applications", vol. 53, 2006, p. 65–84.

[13] C. BORDENAVE. *Spatial capacity of multiple access wireless networks*, in "IEEE transactions on Information Theory", vol. 52, n^{o} 11, 2006, p. 4977–4988.

[14] C. BORDENAVE. *Stability of Spatial Networks*, in "Advances in Applied Probability", vol. 38, n^{o} 8, 2006, p. 487–504.

[15] A. B. DIEKER, M. LELARGE. *Tails for (max, plus) recursions under subexponentiality*, in "Queueing Systems. Theory and Applications", vol. 53, n^{o} 4, 2006, p. 213–230.

[16] D. MCDONALD, J. REYNIER. *Mean field convergence of a model of multiple TCP connections through a buffer implementing RED*, in "Annals Appl. Probab.", vol. 16, n^{o} 1, 2006.

Publications in Conferences and Workshops

[17] F. BACCELLI, N. BAMBOS, C. CHAN. *Optimal Throughput and Routing for Wireless Link Arrays*, in "Proceedings of IEEE Infocom, Barcelona, Spain", IEEE, April 2006.

[18] F. BACCELLI, S. MACHIRAJU, D. VEITCH, J. BOLOT. *The Role of PASTA in Network Measurement*, in "Proceedings of ACM SIGCOMM'06, Pisa, Italy", ACM, October 2006.

[19] F. BACCELLI, D. MCDONALD. *A Stochastic Model for the Throughput of Non-Persistent TCP Flows*, in "Proceedings of ValueTools, Pisa, Italy", October 2006.

[20] F. BACCELLI, D. MCDONALD. *Mellin Transforms for TCP Throughput with Applications to Cross Layer Optimization*, in "Proceedings of CISS, Princeton", Princeton University, March 2006.

[21] T. BONALD. *Throughput Performance in Networks with Linear Capacity Contraints*, in "Proceedings of CISS, Princeton", March 2006.

[22] T. BONALD, A. PROUTIÈRE. *Flow-level stability of utility-based allocations for non-convex rate regions*, in "Proceedings of CISS, Princeton", March 2006.

[23] C. BORDENAVE. *Navigation on Self-Organized Networks*, in "Workshop on Spatial Stochastic Models for Wireless Networks (SPASWIN), Boston", IEEE, April 2006, http://icawww1.epfl.ch/spaswin/1-1.pdf.

[24] S. BORST, A. PROUTIÈRE. *Capacity of Wireless data Networks with Intra and Inter-cell Mobility*, in "Proceedings of IEEE Infocom, Barcelona, Spain", IEEE, April 2006.

[25] P. CHAPORKAR, K. KAR, S. SARKAR. *Achieving Queue Length Stability Through Maximal Scheduling in Wireless Networks*, in "Information Theory and Applications Inaugural Workshop, San Diego CA, USA", invited paper, University of California, February 2006.

[26] N. HEGDE, A. PROUTIÈRE. *Packet and flow-level performance of multi-hop wireless networks*, in "Proceedings of IEEE GLOBECOM, San Francisco", IEEE, November 2006.

[27] J. REYNIER, F. MATHIEU. *Missing piece issue and upload strategies in flashcrowds and peer to peer based file sharing*, in "Proceedings of the International Conference on Internet and Web Applications and Services (ICIW), Guadeloupe, French Caribbean", 2006.

Internal Reports

[28] D. ALDOUS, C. BORDENAVE, M. LELARGE. *Near-Minimal Spanning Trees: a Scaling Exponent in Probability Models*, math.PR, n° 0609547, arXaiv, 2006, http://arxiv.org/abs/math.PR/0609547.

[29] C. BORDENAVE. *Eigenvalues of Euclidean Random Matrices*, RR, n° 5965, INRIA, Rocquencourt, August 2006, http://hal.inria.fr/inria-00089236.

[30] C. BORDENAVE. *Navigation on a Poisson point process*, RR, n° 5790, INRIA, Rocquencourt, August 2006, http://hal.inria.fr/inria-00070231.

[31] C. BORDENAVE, S. FOSS, V. SHNEER. *Un Protocole d'Accès Multiple Aléatoire avec Interactions Spatiales*, RR, n° 5975, INRIA, Rocquencourt, September 2006, http://hal.inria.fr/inria-00090762.

[32] B. BŁASZCZYSZYN, M. K. KARRAY. *Performance Evaluation of Scalable Congestion Control Schemes for Elastic Traffic in Cellular Networks with Power Control*, to appear in Proc. of IEEE Infocom 2007, RR, n^{o} 6077, INRIA, Rocquencourt, December 2006, http://hal.inria.fr/inria-00121767.

[33] B. BŁASZCZYSZYN, B. RADUNOVIĆ. *M/D/1/0 loss system with interference and applications to transmit-only sensor networks*, submitted to IEEE SPASWIN 2007, RR, n^{o} 6073, INRIA, Rocquencourt, December 2006, http://hal.inria.fr/inria-00121481.

[34] M. LELARGE. *Sample path large deviations for queueing networks with probabilistic routing*, math.PR, n^{o} 0602130, arXive, 2006, http://arxiv.org/abs/math.PR/0602130.

[35] M. LELARGE. *Tail asymptotics for monotone-separable networks*, math.PR, n^{o} 0510117, arXive, 2006, http://arxiv.org/abs/math.PR/0510117.

[36] B. RADUNOVIĆ, A. PROUTIÈRE. *On Downlink Capacity of Cellular Data Networks with WLAN/WPAN Relays*, RR, n^{o} 6050, INRIA, Rocquencourt, December 2006, http://hal.inria.fr/inria-00118746.

Miscellaneous

[37] B. KAUFFMANN. *Localisation et routage en coordonnées virtuelles : Répartition de charge et localité des contenus*, Rapport de stage de Master2, ENS, September 2006.

[38] M. PIANCINO. *On Scalable TCP*, Rapport de stage de Master2, Politecnico di Torino, September 2006.

[39] D. YOGESHWARAN. *Poisson-Poisson cluster SINR covrage process*, Master thesis report, IISC, September 2006.

References in notes

[40] F. BACCELLI, B. BŁASZCZYSZYN. *On a coverage process ranging from the Boolean model to the Poisson Voronoi tessellation, with applications to wireless communications*, in "Advances in Appl. Probab", vol. 33, 2001, p. 293–323.

[41] F. BACCELLI, B. BŁASZCZYSZYN, M. K. KARRAY. *Contrôle charge dans le sens montant pour les systèmes de communication sans fil avec contrôle de puissance*, Deposing: INRIA/FT - Cas 43FT, 2003, patent pending FR03 05354.

[42] F. BACCELLI, B. BŁASZCZYSZYN, M. K. KARRAY. *Dispositif et procédé de contrôle de charge avec contrôle de puissance*, Deposing: INRIA/FT - Cas 42FT, 2003, patent pending FR03 05354.

[43] F. BACCELLI, B. BŁASZCZYSZYN, M. K. KARRAY. *Blocking Rates in Large CDMA Networks via a Spatial Erlang Formula*, in "Proceedings of IEEE Infocom, Miami, FL, USA", see also INRIA RR 5517, March 2005, http://hal.inria.fr/inria-00070489.

[44] F. BACCELLI, B. BŁASZCZYSZYN, F. TOURNOIS. *Dispositif et méthode de contrôle d'admission et de congestion de la configuration d'un réseau de communication sans fil*, Deposing: INRIA - Cas 57, 2003, patent pending FR03 02017 and USA 10/414.486.

[45] F. BACCELLI, S. FOSS, M. LELARGE. *Asymptotics of Subexponential Max Plus Networks; the Stochastic Event Graph Case*, in "Queueing Systems", see also INRIA RR 4952, vol. 46, n^o 1–2, 2004, p. 75–96, http://hal.inria.fr/inria-00071627.

[46] F. BACCELLI, K.-B. KIM, D. MCDONALD. *Equilibria of a Class of Transport Equations Arising in Congestion Control*, RR, n^o 5653, INRIA, Rocquencourt, August 2005, http://hal.inria.fr/inria-00070357.

[47] T. BONALD, S. BORST, A. PROUTIÈRE. *Inter-cell scheduling in wireless data networks*, in "Proceedings of European Wireless, Nicosia, Cyprus", April 2005.

[48] T. BONALD, A. PROUTIÈRE. *On the traffic capacity of gaussian broadcast channels*, in "Proceedings of ITC, Beijing", ITC, September 2005.

[49] T. BONALD, A. PROUTIÈRE. *A queueing analysis of data networks*, in "Queueing Networks: A fundamental approach", R. BOUCHERIE, N. VAN DIJK (editors). , to appear, Kluwer, 2007.

[50] C. BORDENAVE, D. MCDONALD, A. PROUTIÈRE. *Random Multi-access Algorithms, A Mean Field analysis*, in "Proceedings of Allerton conference on Communication, Control, and Computing, Allerton, IL", see also INRIA RR 5632, University of Illinois, September 2005.

[51] C. BORDENAVE, D. MCDONALD, A. PROUTIÈRE. *Mean field limits of a system of interacting particles in a rapidly varying environment*, in "Annals of Applied Probability", n^o submitted, 2006.

[52] C. BORDENAVE, D. MCDONALD, A. PROUTIÈRE. *Random multi-access algorithms in networks with partial interaction: A mean field analysis*, in "ITC 20", submitted, 2007.

[53] S. BORST, N. HEGDE, A. PROUTIÈRE. *Combined cell selection and inter-cell scheduling in wireless data networks*, submitted, 2007.

[54] O. DOUSSE, F. BACCELLI, P. THIRAN. *Impact of Interferences on the Connectivity of Ad Hoc Networks*, in "IEEE Trans. Networking", vol. 13, n^o 2, 2005, p. 425–436.

[55] O. DOUSSE, M. FRANCESCHETTI, N. MACRIS, R. MEESTER, P. THIRAN. *Percolation in the signal to interference ratio graph*, in "Journal of Applied Probability", vol. 43, n^o 2, 2006, p. 552–562.

[56] E. N. GILBERT. *Random plane networks*, in "SIAM J.", vol. 9, 1961, p. 533–543.

[57] S. HANLY. *Capacity and power control in spread spectrum macrodiversity networks*, in "Proc. of IEEE Trans. on Comm.", vol. 44, 1996, p. 247–256.

[58] N. HEGDE, A. PROUTIÈRE. *Wireless mesh networks: Performance and design*, in "ITC 20", submitted, 2007.

[59] L. JIAPING, A. PROUTIÈRE, Y. YI, M. CHIANG, V. POOR. *Flow-level stability of networks with non-convex and time-varying rate regions*, in "ACM Sigmetrics", submitted, 2007.

[60] B. KAUFFMANN, F. BACCELLI, A. CHAINTREAU, K. PAPAGIANNAKI, C. DIOT. *Self Organization of Interfering 802.11 Wireless Access Networks*, to appear in Proc. IEEE INFOCOM 07, RR, n^o 5649, INRIA, Rocquencourt, August 2005, http://hal.inria.fr/inria-00070360.

[61] W. KIRSCH, P. MÜLLER. *Spectral properties of the Laplacian on bond-percolation graphs*, in "Math. Z.", vol. 4, 2006, p. 899–916.

[62] M. LELARGE. *Packet Reordering in Networks with Heavy-Tailed Delays*, RR, n^{o} 5783, INRIA, 2005, http://hal.inria.fr/inria-00070238.

[63] S. MACHIRAJU, D. VEITCH, F. BACCELLI, J. BOLOT. *Adding Definition to Active Probing*, in "Computer Communication Review", vol. Submitted, 2006.

[64] L. MASSOULIÉ, J. ROBERTS. *Bandwidth sharing: objectives and algorithms*, in "IEEE Trans. Networking", vol. 10, n^{o} 3, 2002, p. 320–328.

[65] M. MÉZARD, G. PARISI, A. ZEE. *Spectra of Euclidan random matrices*, in "Nuclear Phys B.", vol. 559, n^{o} 3, 1999, p. 689–701.

[66] P. MÜLLER, P. STOLLMANN. *Spectral asymptotics of the Laplacian on supercritical bond-percolation graphs*, Technical report, n^{o} math-ph/0506053, ArXiv, October 2006, http://arxiv.org/abs/math-ph/0506053.

[67] B. RADUNOVIĆ, A. PROUTIÈRE. *Cross-layer design of Mesh networks*, in "Handbook of wireless mesh and sensor networks", submitted, McGraw-Hill, 2007.

[68] D. YOGESHWARAN. *Phase-type distributed power in SINR coverage process*, 2006, Inria summer intern report.

[69] J. ZANDER. *Performance of Optimum Transmitter Power Control in Cellular Radio Systems*, in "IEEE Trans. Veh. Technol.", vol. 41, 1992, p. 57–62.