INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Trec

Network Theory and Communications

Rocquencourt

THEME COM

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1. Team

TREC is a joint INRIA-ENS project-team.

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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 Alcatel, France Télécom, IBM, 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 event and large network asymptotics;
- the development of mathematical tools based on stochastic geometry 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 principal 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. The design of multicast overlays based on these common transport protocols is another line of research that is directly linked to the understanding of the dynamics of these protocols.
- 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.
  We started a new line of enquiry on the self-organization of Wifi mesh networks. The general problem within this context is 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 is primarily interested in 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 link with certain methods of particle systems such as hydrodynamic limits and mean field limits has allowed us to assess the properties of networks of infinite dimension or infinite population, with quite promising implications to the scalability of TCP based overlay networks.

- 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

We interact with the following industrial partners: Alcatel, France Télécom, INTEL, IBM and Sprint.

- The work with Alcatel is part of the "End to End" OSC (Opération Stratégique Conjointe), with the Network Strategy Group of Alcatel Bell, Antwerp. The OSC ended in July 2005 after 4 years of intensive collaboration. The work of the last phase focused on TCP over wireless and xDSL access and has led to a series of Infocom papers. Other activities with Alcatel are pursued jointly with N2NSoft. This concerns DSLAM optimization (with Alcatel Bell Broadband Access) and load balancing in core networks (with RNI Marcoussis).
- The collaboration with France Télécom is structured in two parts:
  - The PRIMO CRC (Partage de Ressources dans l'Internet et les réseaux MObiles). The CRC is focused on teletraffic theory and aims at extending this theory to the classes of communication networks that are used and designed by operators today. The research activity covers both wireline and wireless networks. The main mathematical tools to be investigated within this context are queueing theory, information theory and stochastic geometry.
  - The CRE 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 started the implementation of some our methods in its own dimensioning tools.
- The work with INTEL Cambridge (UK) is focused on the design of self organization protocols in wifi mesh networks. This lead to a joint paper and to an INTEL patent with INRIA-ENS co-authors.
- With IBM, we work on the design of multicast overlays, both with and without backpressure mechanisms. This lead to a series of Infocom papers; IBM also filled two patents on the matter with INRIA-ENS co-authors.
- The interaction with Sprint ATL (USA) primarily bears on the design of active probing methods for the estimation of internal properties of core or access networks based on end-to-end measurements. This lead to a first joint paper and to a wealth of ongoing projects on the matter, also involving Prof. Darryl Veitch of Melbourne.

5. Software

5.1. Netscale

Keywords: *HTTP traffic*, *TCP*, *access router*, *core router*, *quality of service*, *simulation*.

Participants: François Baccelli, Dohy Hong [N2NSoft].

Based on the hybrid simulation methodology of the interaction of a large number of TCP connections designed by TREC, a software tool was developed. The tool allows one to study the characteristics of the rates obtained by each type of user or application under realistic assumptions on traffic (mixing HTTP, Voice, Mail, Video etc) from a detailed description of each network element. This simulation activity was transferred to the start-up N2NSOFT (http://www.n2nsoft.com) created by D. Hong. Currently TREC participates in the adaptation of this methodology to the simulation of new dynamic routing algorithms in core networks within the framework of a collaboration with Alcatel Marcoussis.

5.2. Multicast Overlay Prototype

Keywords: *overlay multicast*, *web*.

Participant: Augustin Chaintreau.

A simulation prototype was designed by A. Chaintreau for the simulation of large multicast overlay networks (see Section 6.1.2). An experimental PlanetLab platform for such overlays was developed and tested in collaboration with IBM.

5.3. 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 [17]. 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*, *DSL*, *IP*, *Reno*, *TCP*, *Tahoe*, *additive increase multiplicative*, *bit error*, *congestion prevention/control*, *decrease algorithm*, *delay compensation*, *feedback control*, *hybrid system*, *multicast*, *packet error*, *simulation*, *stability*, *synchronization*, *transmission error*, *wireless AIMD flow model*.

Participants: François Baccelli, Augustin Chaintreau, Rene Cruz [UCSD], Danny De Vleeschauwer [Alcatel Bell], Ki-Baek Kim, Zhen Liu [IBM Research], David McDonald, Antonio Nucci [Sprint & Narus], Julien Reynier, Anton Riabov [IBM Research].

Operators require a methodology for analysing traffic and congestion control mechanisms to do resource planning (buffer capacities and bandwidth) capable of handling every possible mix of traffic (voice, video and data) in order to ensure predefined end to end QoS bounds. Several research directions were pursued.

6.1.1. Mean Field Analysis of Interacting TCP Flows

Mean field limits have allowed us to assess the properties of networks with many sources.

6.1.1.1. Mean field model for interacting HTTP flows.

In [38], we discussed the mean field limit of a model for multiple HTTP sources multiplexed through a drop-tail router. 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.

These results were further understood by an analysis based on a PDE evolution equation of the instantaneous distribution of rates. It was possible to prove in this setting that such a phenomenon is present for an old version of the TCP protocol (TCP Tahoe). The argument of the proof does not apply in the same form for the current dominant version of TCP (TCP Reno) although the numerical evidence remains. Simulations with a discrete event simulator were further conducted to show that this phenomenon may also be present in the packet-level dynamics of the TCP protocol.

In the prelimit with a finite number of sources the above regimes merge into a single metastable regime: we observe rare transitions between the fluid interactionless regime and the turbulent interaction regime. In the paper [44], we outlined a general framework for describing these metastable regimes.

The AQM case was also studied in [45]. In this paper, we derived a closed form formula for 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. We also derive closed form expressions for the mean time to transfer a file and for the distribution of the transmission rate. Several distributions for the file sizes and idle times are considered including heavy tailed distributions. The formula for the mean transmission rate is shown to boil down to the classical square root mean value formula for persistent flows when the average file size tends to infinity. 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. Mean field analysis of TCP flows with transmission errors and congestion losses.

In [43], we analyzed the performance of a large population of a single class of long lived TCP flows experiencing random packet losses due to both random transmission errors and congestion created by the sharing of a common tail drop bottleneck router.

In [19], we then analyzed the performance of a large population composed of several classes of long lived TCP flows experiencing packet losses due to random transmission errors and to congestion created by the sharing of a common tail-drop or AQM bottleneck router. Each class has a different transmission error rate. This setting is used to analyze the competition between wired and wireless users in an access network, where one class (the wired class) has no or small (like BER in DSL) transmission error losses whereas the other class has higher transmission error losses, or the competition between DSL flows using different coding schemes. We proposed a natural and simple model for the joint throughput evolution of several classes of TCP flows under such a mix of losses. Two types of random transmission error losses are considered: one where losses are Poisson and independent of the rate of the flow, and one where the losses are still Poisson but with an intensity that is proportional to the rate of the source. We showed that the large population model where the population tends to infinity has a threshold (given in closed form) below which there are no congestion losses at all in steady state, and above which there is a stationary limiting regime in which we can compute both the mean value and the distribution of the rate obtained by each class of flow. We also showed that the maximum mean value for the aggregated rate is achieved at the threshold.

In [30], we also 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 can also be used, 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 the class of transport equations arising in the context of TCP.

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 [31]. 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 [31], 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.

6.1.1.4. 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 [64] provides a new approach to this mean field convergence problem. This publication will be published by the Annals of Applied Probability in January 2006 as [65]. This approach which first allowed us to analyse RED is now being extended to the case of non persistent sources through one router. Recently this methodology was extended to a wide class of problems including HTTP on/off sources modeled by the model in [38]. This extension is a part of the PhD [68].

6.1.2. Scalability of TCP based Multicast Overlays

6.1.2.1. The one to many TCP overlay.

The study of multicast group communication supported by an overlay network was published this year. In this type of architecture the datas are sent by the source to a first set of end-systems using distinct TCP connections; these end-systems in turn transmit the data to a further set of end-systems, through new and distinct TCP connections. The forwarding mechanism between end-systems is thus organized in a tree rooted at the source.

We have analyzed the properties of the group communication on such an overlay network, focusing on reliability and throughput performance in the case where the memory available in each end-systems is finite. Buffer overflows may occur at intermediate end-systems as TCP connections used further in the tree may not be able to transmit data at the same speed as that of the input of the end-system. These losses must be prevented and the throughput should therefore be adapted in a scalable way.

- We have shown that this scheme can be made reliable with a small addition to the current TCP implementation : a local constraint on the communication, called back-pressure, that allows an end-system to stop the emission of packets by upstream nodes when his local-memory is full. This modification may have a great impact on the performance of the system, in particular if the group is very large, as long delays or degraded network conditions in any link can impact the throughput of data everywhere in the tree.

- We were able to prove that such overlays are scalable in the sense that the group throughput is bounded from below by a positive constant that does not depend on the size of the group. This result was obtained using a technique of first-passage percolation on random graphs under the following assumptions: the multicast tree has a bounded degree, perturbations due to cross traffic are light tailed and independent in time.
- Another possible cause of unreliability for this scheme is the failure of an end-system, as the communication relies on a collaborative scheme. We have proved that if the maximal number of simultaneous failures is bounded, the tree is able to recover all the lost pieces of information, and to reconfigure its topology with the same maximal degree. This comes at the cost of an additional finite backup memory in each end-system.

This work, made in collaboration with the research group "Systems and Optimization" of IBM Waston T.J. laboratory, resulted in the proposal of an architecture named "The one-to-many TCP Overlay". This architecture has been patented and the research, completed in 2004, has been published this year in [18].

6.1.2.2. Last-passage percolation and infinite discrete event systems.

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 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 graphs, 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 [58], to be defended early next year, they will be submitted soon for publication in a journal.

6.1.3. 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 flashcrowds phase, and scalability may fail. Even "smart" networks can encounter the whole file but one piece downloaded case, which we call starvation. In [67], we suggest 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.

6.2. Design and Performance Analysis of Wireless Networks

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

Participants: François Baccelli, Bartek Błaszczyszyn, Thomas Bonald, Charles Bordenave, Sem Borst [CWI/Bell Labs], Serguei Foss [Heriot Watt University], Nidhi Hegde [FT R&D], Mohamed Karray [FT R&D], Franck Lebeugle [FT R&D], David McDonald, Paul Muhlethaler [INRIA HIPERCOM], Alexandre Proutière, James Roberts [FT R&D], Vsevolod Shneer [Heriot Watt University], Minh Anh Tran.

This axis concerns the analysis and the design of wireless communication networks, in particular CDMA/UMTS and ad hoc networks. We are interested both in macroscopic models, which are particularly

important for economic planning and in models allowing the definition of optimized protocols. Our approach combines several tools and in particular stochastic geometry.

6.2.1. Admission/Congestion Control and Maximal Load in Large CDMA Networks

This work is focused on the influence of geometry on the combination of inter-cell and intra-cell interferences in the downlink of large CDMA networks. We used an exact representation of the geometry of the downlink channels to define scalable admission and congestion control schemes, namely schemes that allow each base station to decide independently of the others what set of voice users to serve and/or what bit rates to offer to elastic traffic users competing for bandwidth. We studied the load of these schemes when the size of the network tends to infinity using stochastic geometry tools. By load, we mean the distribution of the number of voice users that each base station can serve and that of the bit rate offered to each elastic traffic user.

In our approach, the location of both the antennas and the mobiles is represented by point processes on the plane. The necessary and sufficient condition for the feasibility of the uplink and the downlink, globally in the network, is related to the spectral radius of some random, infinite matrix of the path loss, whose entries depend on the locations of the points of both point processes. In a first article [48], we proposed a sufficient condition for the feasibility of the downlink power allocation, that is based on the sub-stochasticity of the path loss matrix. This approach permits the analysis of the load of each base station cell in a decentralized way, considering only its own users and locations of other base stations. In certain cases, for example for the Poisson point process of antennas and mobiles, this approach gives an explicit closed form solution for the mean global capacity of the network. In particular, given the density of the base stations we found the density of the users that can be served by the network. The approach adopted in this paper leads to some decentralized admission and congestion control schemes. These protocols are the basis of an INRIA patent.

In [37], our approach was extended to the uplink and took into account the existence of maximal power constraints of the base stations and users. Moreover, in hexagonal network, using Gaussian approximations for the total load imposed on a given cell by all users served in it, we gave explicit formulas for the infeasibility probability; i.e., for the probability that a Poisson population of a given intensity cannot be entirely accepted by the base station running our admission control protocol. The refinement of the admission and congestion control protocols that take into account maximal base station powers and user powers in both uplink and downlink lead to two joint INRIA-France Telecom patents.

In [49], we extended our model to take into account the scenario 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 still 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. Indeed, 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 [60] 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.

6.2.1.1. Blocking rates via a spatial Erlang formula.

In [17], [29], we showed that the notion of infeasibility probability is closely related to the notion of blocking probability; i.e., to the fraction of users that are rejected by the admission control policy in the long run, a notion of central practical importance within this setting. The relation between these two notions is not bound to our particular admission control schemes, but is of a more general nature, and in a simplified scenario can be identified with the well-known Erlang loss formula. Namely, the feasibility probability (i.e., the complement of the infeasibility probability) is the normalizing constant (called also the partition function) in the classical loss formula for a general loss network. We proved this relation using a general spatial birth-and-death process, where customer locations are represented by a spatial point process that evolves over time as customers arrive

or depart. This allows our model to include the exact representation of the geometry of inter-cell and intra-cell interferences, which play an essential role in the load indicators used in these cellular network admission control schemes.

Our spatial Erlang formula together with previously developed explicit formulas for the feasibility probability, allows for analytical expressions of the fundamental relations between key engineering parameters of the CDMA network and the performance metrics. These relations make possible more systematic studies of several important practical questions concerning QoS, capacity and dimensioning of the network. Their pertinence has already been recognized by Orange. This operator implemented the spatial Erlang formula in its own dimensioning tools.

6.2.1.2. Stability of data flows on a CDMA network.

Wireless networks provide new models for queuing theory. A process of users arrives in the network and each user wants to receive data from the network before leaving the system. The key feature is the maximum number of bits per surface unit and time unit the network can handle without saturation.

Following the results presented in the research report [50], a paper has been submitted and accepted in Advances in Applied Probability.

6.2.2. Downlink Capacity of Wireless Data Networks

6.2.2.1. Comparing traffic capacities with different access technologies.

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 we defined the cell capacity as the maximum traffic intensity such that the system remains stable. We applied this notion of various technologies including TDMA, CDMA and OFDM, and compared the results to the maximum capacity given by the information theory [22].

6.2.2.2. Inter-cell scheduling and cell selection.

In [20] and [51] 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 a s 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 loads across cells.

6.2.3. Impact of Mobility and Fading on Network Capacity

6.2.3.1. Cellular networks supporting real-time applications.

The outage probability is a key performance measure for real-time traffic in wireless networks, often considered as even more critical than the blocking probability. The blocking and outage probabilities do not have closed-form expressions as they depend in a too complex way on the traffic characteristics (call duration, bit rate requirement), the radio conditions (fading, shadowing, noise, interference) and the considered admission and outage policies. In [21], we derived upper bounds for the blocking and outage probabilities for general traffic characteristics and radio conditions under the mild assumption that the admission and outage policies satisfy a certain monotonicity property. These conservative estimates may depend on call

characteristics like the bit rate requirement and the trajectory of the mobile. The results were applied to the uplink and the downlink of CDMA networks.

6.2.3.2. Cellular networks supporting data traffic.

The performance of wireless data systems has been thoroughly studied in the context of a single base station. In [52], 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.

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

6.2.4.1. User-level performance in WLAN hotspots.

In [25], we presented a novel performance analysis of the downlink of WLANs carrying TCP traffic. We first provided a packet level analysis that accounts not only for the interaction between TCP and the IEEE 802.11 MAC protocol, but also for the different radio conditions experienced by various users. We then studied the quality of service as perceived by users, i.e., we characterize the mean transfer time of data flows (web pages, files, etc.). The latter performance metric and its evaluation can then be used to design efficient dimensioning rules. The derived analytical results were validated through simulations.

6.2.4.2. Voice capacity of 802.11 WLAN under distributed control.

Though initially designed for data transport, there is increasing interest in using the 802.11 WLAN protocol for voice and other real time services. In [24], we presented a performance model for voice over WLAN under distributed control. The model is based on classical decoupling arguments and allows an analytical evaluation of network capacity in terms of tuneable protocol parameters. We determined parameter settings that maximize the number of simultaneous conversations and demonstrated the significant impact on capacity of the voice packet size. Models were developed for both dedicated and integrated networks using the priority features of 802.11e.

6.2.4.3. A mean field analysis of random multi-access algorithms.

Using mean field techniques, we presented in [23], [32] 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. We proved that when the number of sources grows large, the system is decoupled, i.e., source behaviors become mutually independent. These results were applied in the specific case of exponential back-off algorithms, where the transient and stationary distributions of the back-off processes are explicitly characterized. This work provides a theoretical justification of decoupling arguments used by many authors, e.g. Bianchi, to analyze the performance of random algorithms in Wireless LANs.

6.2.5. Self-Organizing of 802.11 Access Networks

The increased 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 efficiently share the spectrum.

In [33], we proposed a set of distributed algorithms, for different elements of a wireless access networks (access points, users), to efficiently use today's diversity proposed by 802.11 specifications and hardware,

for data download traffic. 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 [63]. We established the mathematical properties of the proposed algorithms and studied their performance using analytical, event-driven simulations. wireless access networks. 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.

6.2.6. Mobile ad Hoc Networks

The exact representation of signal to interference ratio based on stochastic geometry has shed light on problems of central importance in MANETs

- Connectivity that is most often analyzed under (over)simplified Boolean model representations, is in fact not always improved by densification as shown with O. Dousse and P. Thiran of EPFL in [12];
- MAC protocols can be optimized for maximizing the network total transport capacity as shown via a collaboration with P. Muhlethaler of Hipercom that is again based on additive and maximal shot noise representations of interferences.
- Stability of decentralized access protocols in such networks is an important and difficult problem. In collaboration with Serguei Foss and Vsevolod Shneer (Heriot Watt Univ.), we analyze the stability of an Aloha-type access protocol with a simplified form of spatial interactions.

6.2.6.1. Connectivity in MANETs.

In the paper [12], we studied the impact of interferences on the connectivity of large-scale ad-hoc networks using percolation theory. We assumed that a bi-directional connection can be set up between two nodes if the signal to noise ratio at the receiver is larger than a certain threshold. The noise is the sum of the contributions of interferences from all other nodes, weighted by a coefficient γ representing an orthogonality factor and of a background noise. We found that there is a critical value of γ above which the network is made of disconnected clusters of nodes. We also proved that if γ is non zero but small enough, there exist node spatial densities for which the network contains a large (theoretically infinite) cluster of nodes, enabling distant nodes to communicate in multiple hops.

6.2.6.2. An Aloha protocol for multihop mobile wireless networks.

In [47], we defined an Aloha type access control mechanism for large mobile, multihop, wireless networks. The access scheme is designed for the multihop context, 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. First, its transport capacity is proportional to the square root of the density of mobiles and its stability can be shown under mobility conditions discussed in this paper. The delay provided by this protocol for transporting information from one node to any another node is proportional to the distance between them and to the square root of the network density. Furthermore this protocol is self adapting to the network density; more precisely 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.

6.2.6.3. Stability of a random access protocol with spatial interaction.

We analyzed the stability of an access protocol with spatial interaction. The model is designed to fit with decentralized wireless communications systems. At each time slot, some users arrive in the network at a given location. Each user in the system accesses a common channel randomly and a user leaves the system if it the only user accessing the channel in a local neighborhood. We are currently writing part of this work for a first publication.

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], Ki-Baek Kim, Sridhar Machiraju [Berkeley and Sprint ATL], David McDonald, Serguei Foss [Heriot Watt University], Marc Lelarge, Alexandre Proutière, Darryl Veitch [University of Melbourne].

6.3.1. Insensitivity Property of Queueing Networks

In modern computer-science and telecommunication networks, it is desirable to share the resources so that, as for telephone networks, the performance of these systems does not depend on the fine characteristics of the traffic generated by users. Such resource allocations can be derived from so-called Whittle queueing networks whose stationary distribution is known to be independent of the service time distribution at each queue. An application to the dimensioning of IP access networks is presented in [9].

We aim at extending the class of insensitive queueing networks to more general service disciplines. We proved that this class includes the symmetric service disciplines of Kelly with additional random permutations of customers. We also identified a non-symmetric service discipline for which the insensitivity property holds. The characterization of the entire set of insensitive service disciplines remains an open issue.

6.3.2. Stability of Overloaded GPS Queues

In [5], we constructed the stationary workload at each queue of a GPS system under fairly general stochastic assumptions, namely stationarity and ergodicity. This construction is quite simple in the case $\rho < 1$ where ρ is the total load of the system. In the case $\rho \geq 1$, we showed that there are still some queues that can be stable in the following sense: for any initial condition the workload process of these queues couples in finite time with an unique stationary workload process. For the unstable queues, we showed the existence of a mean service rate and gave its expression in closed form.

6.3.3. Large Deviations of Monotone Separable Networks

In [5], we derived tail asymptotics for the supremum of an independent subadditive process as a function of the logarithmic moment generating function. We used this analysis to obtain large deviations results for queueing networks in their stationary regime. In the particular case of (max,plus)-linear recursions, the rate of exponential decay of the stationary solution can be explicitly computed.

6.3.4. Heavy Tail Asymptotics and Long Range Dependence

The theory of rare events for subexponential networks was developed (almost from scratch) via a 4 year long collaboration between TREC and S. Foss. This was one of the main topics of the thesis of Marc Lelage [5] on rare events in networks. Among the main results, we would quote the tail behavior of the end to end delay in max plus networks, and the tail behavior of workload in generalized Jackson networks, together with new developments on networks of the same classes based on fractional Gaussian processes.

6.3.4.1. Asymptotics of subexponential max-plus networks: the stochastic event graph case.

In a joint work with Serguei Foss from Heriot-Watt University [42], we calculated the exact tail asymptotics of stationary response times for open stochastic event graphs, in the irreducible and reducible cases. These networks admit a representation as (max,plus)-linear systems in a random medium. We studied the case of

renewal input and i.i.d service times with subexponential distributions. We showed that the stationary response times have tail asymptotics of the same order as the integrated tail of service times. The multiplicative constants only involve the intensity of the arrival process and the (max,plus)-Lyapunov exponents of certain sequences of (max,plus)-matrices associated to the event graph.

With Ton Dieker [59], we extended these results. 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.

6.3.4.2. Tails in generalized Jackson networks with subexponential service distributions.

In the case of generalized Jackson networks, we focused on a key state variable, already used in the past for determining the stability region of such networks [41], which is the time to empty the network after stopping the arrival process. We studied the case of renewal input, Markovian routing and i.i.d. service times with subexponential distributions. In a joint work with Serguei Foss [7], we derived the exact asymptotics for the tail of this state variable in the stationary regime.

6.3.5. Fluid Stochastic Networks

In [15], we used a sample-path technique to derive asymptotics of generalized Jackson queueing networks in the fluid scale, namely when space and time are scaled by the same factor n. The analysis presupposes only the existence of long-run averages and is based on some monotonicity and concavity arguments for the fluid processes. The results provide a functional strong law of large numbers for stochastic Jackson queueing networks since they apply to their sample paths with probability one. The fluid processes were shown to be piece-wise linear and an explicit formulation of the different drifts is given. In particular, this fluid limit gives a simple computation of the constant $\gamma(0)$ that appears in the stability condition for such networks as demonstrated in [40].

6.3.6. Queueing Theory for Active Probing

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. In the paper [26], [36], 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.

6.3.7. Receding horizon control for linear systems with polytopic uncertainty

In [34], we propose a new robust receding horizon control scheme for linear input-constrained discrete-time systems with polytopic uncertainty. We provide a rigorous proof for closed-loop stability. The control scheme is based on the minimization of the worst-case cost with time-varying terminal weighting matrices, which can easily be implemented by using linear matrix inequality optimization. We discuss modifications of the proposed scheme that improves feasibility or on-line computation time. We compare the proposed schemes with existing results through simulation examples.

6.4. Point Processes and Stochastic Geometry

Keywords: *Bartlett spectral measure, Boolean model, Hawkes process, Voronoi tessellation, dead-leaves model, double-stochastic Poisson Process, multicast, non-homogeneity, spatial point process, spatial trees.*

Participants: François Baccelli, Pierre Brémaud, Bartek Błaszczyszyn, Charles Bordenave, Yann Gousseau [ENST], Laurent Massoulié [Microsoft Cambridge], Emmanuel Roy, René Schott [University of Nancy], Andrea Ridolfi [EPFL], Fançois Roueff [ENST], Giovanni Luca Torrisi [CNR, Rome].

This year our work is focused on spectral analysis of point processes and approximations of non-homogeneous Voronoi tessellations, percolation and sensitivity analysis of Poisson driven Stochastic systems, as well as spatial Markov queueing networks.

6.4.1. Second Order Properties of Random Fields and of Point Processes

This axis concerns spectral analysis of processes related to point processes: random sampling processes, shot noises, and the point processes themselves, for example Hawkes processes or point processes with clusters. In [53], [54] and [10], we have presented general formulas for Cramer or Bartlett power spectral measures with respect to a point process that is not necessarily a Poisson, renewal, or Cox, but a general stationary point process whose Bartlett spectrum is known. Such a generality is needed in many circumstances. For example, using the results of this basic theoretical research, in [55], [56], we present the calculation of the spectra of complex signals used in ultra-wide bandwidth.

6.4.2. Poisson Measures, Infinite divisibility and Ergodic Properties

In [69], [27] and in his PhD Thesis [6], Emmanuel Roy has investigated ergodic properties of infinitely divisible (ID) objects such as Poisson measures, ID random measures and ID stationary stochastic processes without Gaussian component. The ergodic theory of these probabilistic systems is closely related to infinite measure ergodic theory, the link between the two being the so-called Lévy measure. Once ergodic behaviors of Poisson measure are elucidated, it is easy to derive equivalent results for ID stationary processes without Gaussian part thanks to Maruyama's representation of these processes as stochastic integral against a well chosen Poisson measure. The generic Poissonian automorphism (in terms of Baire categories) is studied and proved to be weakly mixing, rigid and with simple spectrum. A whole chapter (in collaboration with Patricia Reynaud-Bouret) is devoted to a detailed study of an important class of ID point processes (Hawkes processes) which appear in genetics and seismology. In particular, non-asymptotic estimates are given for important functionals of these processes in order to elucidate their statistical properties useful in the applications.

6.4.3. Approximate Decomposition of Modulated-Poisson Voronoi Tessellations

Approximate decomposition is a technique of the approximation of the inhomogeneous models by the results obtained for the homogeneous ones. Mathematical formalization of this technique requires estimations of the errors of approximation.

In [11], we considered the Voronoi tessellation of Euclidean plane that is generated by an inhomogeneous Poisson point process whose intensity takes different constant values on sets of some finite partition of the plane. We showed that mean functionals of a cell with the nucleus located in a given set of the partition can be approximated by the mean functionals of the typical cell of the homogeneous Poisson Voronoi tessellation with intensity appropriate to this partitioning set. We gave bounds for the approximation errors, which depend on the distance of the nucleus to the boundary of the element of the partition it belongs to. In the case of a stationary random partition, we showed that mean functionals of the typical cell of the respective double-stochastic Poisson-Voronoi tessellation admit an approximate decomposition formula. The true value is approximated by a mixture of respective mean functionals for homogeneous models, while the explicit upper bound for the remaining term, which depends on the covariance functions of the random partitioning elements, can be computed numerically for a large class of practical examples. This paper complements the previous studies in [57], where the distribution of the typical cell is approximated. One of the motivations for the study in question is modeling of modern communication networks, where application of the Poisson Voronoi tessellation has already proven to give some interesting results and where the assumption of the homogeneity is often non-adequate.

6.4.4. Random Spanning Tree

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.

Local functionals such as the length of a directed edge or the mean degree can be computed explicitly and the limits of local functionals can be expressed in terms of a limiting forest: the directed spanning forest. We have also proved a law of large numbers on the average over a semi-infinite path in the RST and established the convergence of the spatial average of the length of the edges. Some topological results have also been proved, namely a shape theorem for the set of vertices of generation less than k and the number of semi-infinite paths.

This work led to a research report [28], a publication in the proceedings of the 43th Allerton conference [16] and a to submission to Annals of Applied Probability.

6.4.5. Monte Carlo Methods for Sensitivity Analysis of Poisson Driven Stochastic Systems

With Giovanni Luca Torrisi we worked on the computation of the derivatives of functionals of Poisson point process. We derive Monte Carlo methods to estimate these derivatives. This work is motivated by the sensitivity analysis of 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. We are currently writing a paper for publication.

6.4.6. Spatial Markov Queueing Processes with Applications to Wireless Loss Systems

In [46], we considered a pure-jump Markov generator which can be seen as a generalization of the spatial birth-and-death generator, which allows for mobility of particles. Conditions for the regularity of this generator and for its ergodicity were established. We also gave the conditions under which its stationary distribution is a Gibbs measure. This extends previous work in [66] by allowing particle mobility. Such spatial birth-mobility-and-death processes can also be seen as generalizations of the spatial queueing systems considered in [70]. So our approach yields regularity conditions and alternative conditions for ergodicity of spatial open Whittle networks, complementing the results in [61].

Our results can be used to model wireless communication networks. In particular we studied two spatial loss models for which we established an expression for the blocking probability that might be seen as a spatial version of the classical Erlang loss formula. Some specific applications to CDMA (Code Division Multiple Access) networks were also discussed (see also paragraph on Erlang formula in section 6.2.1).

7. Contracts and Grants with Industry

7.1. CRE with France Télécom R&D

Participants: François Baccelli, Bartek Błaszczyszyn, Charles Bordenave, Mohamed Kadhem Karray, Jean-Marc Kelif, Mathieu Monfalet, Minh Anh Tran.

Contrat de recherche externalisée (CRE) with France Télécom R&D RESA (ex DMR) represented by Mohamed Kadhem Karray, Jean-Marc Kelif and Mathieu Monfalet entitled “Strategies for the densification of the UMTS network” was signed in 2004 and realized in 2004/2005.

In 2003 TREC proposed a mathematical analysis of the interference in the context of the power control used in CDMA networks. This approach, enriched since this time (see section 6.2.1) in collaboration with researchers from FT R&D, has lead to the definition of a new class of admission and congestion control algorithms. Three patents have been filed on this subject. 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. It is in this sense that our approach is also pertinent to the process of the UMTS network engineering (planning, densification).

The work realized in CRE 2004/2005 is part of a *general perspective of studies leading to the enrichment, validation, refinement and the analysis of possible assets of this novel approach*. In this vein, the present

works of CRE constitute a continuation of those undertaken in CRE 2003 and their extension to 2006-2007 is considered. They also complement studies pursued in a spontaneous collaboration between TREC and the researchers of FT R&D.

The main activity in 2005 was the analysis of the pertinence of the model to the process of the UMTS engineering in order to propose a strategy of the network densification and parameterization. FT R&D continued to implement certain analytical methods proposed within this context in an interface module compatible with other tools of Orange.

7.2. Opération Stratégique Conjointe with Alcatel Bell " End-to-end performance evaluation of packet communication networks”

Participants: François Baccelli, Augustin Chaintreau, Danny De Vleeschauwer, Dohy Hong, Ki Beak Kim, David Mc Donald, Julien Reynier.

This project proposes to develop a general methodology for the analysis of the end to end behavior of key IP applications, including both TCP and UDP applications over large networks.

The main scientific questions concern the evaluation/prediction of the end to end performance (mean values and fluctuations of throughput, delay and loss) obtained by individual TCP controlled (resp. UDP) applications under various potential access modes: xdsl, wireless, optical burst etc. and under various IP backbone loading assumptions.

The activities of the current phase are structured in several joint subprojects with researchers of the Network Strategy Group of Alcatel:

- Long lived TCP flows on drop tail wireless access links [43], presented at IEEE Infocom 04, Hong Kong;
- HTTP flows on drop tail access links [38], presented at ACM Sigmetrics 04, New York;
- Competition of DSL and wireless long lived TCP flows on both drop tail and AQM access links IEEE Infocom 05, Miami [19].
- HTTP flows on AQM access links [45], presented at QoS IP 05, Catania.

The main direction of research investigated this year within the OSC is that of heterogeneity. Other directions include the analysis of AQM networks, a better understanding of finite population models and the design of more accurate statistical models for emerging applications.

Other activities have spined off from the OSC with other groups outside NSG:

- On the analysis of xDSL Networks with the Broadband Access BU of Alcatel Bell.
- On the analysis of load balancing algorithms in core IP networks with RNI Marcoussis.

The OSC has allowed us to hire K.B. Kim and to invite D. Mc Donald who spent six more months with TREC from January 2005.

7.3. IBM Academic Awards

Participants: François Baccelli, Augustin Chaintreau, Marc Lelarge.

TREC was awarded two IBM Academic Awards to work on overlay networks and on wireless networks. These awards were granted for 2004 and 2005 in relation with the collaboration with the group of Z. Liu of IBM Research, T.J. Watson center, Hawthorne NY. Three publications have been prepared in relation with these awards so far:

- an article [39], which bears on the infinite memory case, was presented at IEEE Infocom 04 in Hong Kong;
- the paper [62], which bears on the analysis of networks with self similar cross traffic, which was also be presented at IEEE Infocom 04;
- a third paper on overlay multicast [18] which bears on the case with backpressure and which was presented at IEEE Infocom 05.

A prototype was designed and tested. Two IBM patents (with 2 INRIA co-authors) were filled.

7.4. Sprint ATL

Participants: François Baccelli, Jean Bolot [Sprint ATL], René Cruz [UCSD], Marc Lelarge, Antonio Nucci [Sprint ATL & Narus], Sridhar Machiraju [Berkeley & Sprint ATL], Darryl Veitch [Melbourne University].

The interaction with the research lab of Sprint (Sprint ATL, in Burlingame, Califorina) has 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 [26] 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 [30], 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 involving M. Lelarge have been started on the architecture of heterogeneous wireless networks.

7.5. “Pôle de compétitivité” SYSTEM@TIC Paris-Region

Participants: François Baccelli, Bartek Błaszczyszyn, Dohy Hong [N2N SOFT], Denis Rouffet [Alcatel CIT].

TREC participated in the creation of the “Pôle de compétitivité” SYSTEM@TIC Paris-Region (http://www.systematic-paris-region.org/). The general objectives for the next three years of the sub-project “Usages, Services et Réseaux Intégrés (USRI)” (theme Télécom) supervised by Alcatel CIT are:

- To conceive, develop and integrate into various layers (network, services, terminals and applications) solutions facilitating utilization of complex and heterogeneous systems of IP high-throughput communication.
- Demonstrate these solutions on experimental pilot sites.

Trec contributes to this subproject proposing the following research subjects:

- interaction between TCP and UDP flows,
- development of the TCP-friendly multicast overlays,
- integration of large sensor networks,
- analysis of interferences and coverage in the context of the power control algorithms used in wireless access networks.

The constitutive assembly of the consortium took place in September 2005.

8. Other Grants and Activities

8.1. Networks and International Working Groups

- 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 is the coordinator of the INRIA participation to this NoE.
- Ch. Bordenave is a member of a working group on stochastic geometry that obtained a *MathStic* funding for 2004-2005.

9. Dissemination

9.1. Animation of the Scientific Community

9.1.1. Invited Scientists

- **Professor David McDonald** was visiting TREC on sabbatical leave from the University of Ottawa from June 2003 until June 2005 (except for September to December 2004).
- **Dr Bozidar Radunovic** joined TREC as a post-doctoral fellow in November 2005. In his research project, he will focus on architectures and performance analysis of cellular and ad-hoc wireless networks and specifically on:

  - performance of next generation cellular networks with relays. In such networks, in order to increase the coverage or enlarge the throughput, mobile nodes are allowed to relay messages for other mobile nodes. This scenarios are particularly useful in suburban areas that are not well covered with base stations, or extremely dense areas where the network capacity becomes a limiting factor. The study of different architectures of such networks and their fundamental performance limits is planed.
  - performance of different types of ad-hoc networks with regular architectures (lines, grids), which may occur in organized environments (e.g. Manhattan grid, regular sensor networks). One will analyze how small perturbations in such architectures can affect system performance. One will also study cross layer design issues in wireless sensor networks based on UWB (ultra-wide band) physical layer. This is a new and emerging physical layer technology, particularly promising for sensor networks due to its high positioning accuracy. There, the issue of cross-layer design in such a network is not well understood and it is shown that a careful cross-layer can bring significant performance improvements.

- **Dr Prasanna Chaporkar** joined TREC as a post-doctoral fellow in December 2005.

9.1.2. TREC's seminar

the following scientists gave talks in 2005:

- France
  - Julien Reynier from ENS – Paris talking on "Champ Moyen pour des Flots HTTP", November 29,
  - Anne-Marie Kermarrec from INRIA-IRISA, talking on "SplitStream: high-bandwidth content streaming/distribution system", November 28,
  - Laura Cottatellucci from INRIA MAESTRO talking on "Large CDMA Systems with Linear Multiuser Detectors and Correlated Spatial Diversity : A Simple Representation for Cross-Layer Design", November 18,
  - Emmanuel Roy from ENS / Université Pierre et Marie Curie – Paris talking on "Théorie ergodique des processus de Poisson", June 3,
  - Marc Lelarge from INRIA-ENS TREC talking on "Événements rares dans les réseaux" February 1,
  - Pierre Calka from UFR de Mathématiques et Informatique, Université René Descartes Paris V, talking on "Résultats asymptotiques pour les enveloppes convexes aléatoires et la mosaïque de Poisson-Voronoi", January 28.
- Europe
  - Marc Lelarge from University College – Cork, Ireland / ENS – Paris talking on "Tail asymptotics of sub-additive processes and queueing networks", December 1,
  - Serguei Foss from Heriot-Watt University, Edinburgh, on "Lower Limits and Equivalences for Convolution Tails" on July 07,
  - Bozidar Radunovic from EPFL – Lausanne / INRIA-ENS-Paris talking on "Power Control is Not Required for Wireless Networks in the Linear Regime", June 6,
  - Gianluca Torrisi , CNR, Rome , lectures on "Topics in rare events simulation" April 11, 13, 15,
  - Vsevolod Shneer from University of Heriot Watt, Edinburgh, GB, talking on "Asymptotics for the tail distribution of the maximum of a Markov-modulated random walk with heavy-tailed increments," February 17,
  - Laurent Massoulié from Microsoft – Cambridge, GB, talking on "Network Epidemics," February 17 ,
  - Onno Boxma from University of Eindhoven et Eurandom, The Netherlands talking on "Sojourn times in queueing networks", January 24,
  - Neil O'Connell from The Boole Centre for Research in Informatics, University College Cork, Ireland talking on "Path-transformations associated with queues and Coxeter groups", January 24.
- America, Asia and Australia
  - Corinne Touati from University of Tsukuba, Japon talking on "Application de la théorie des jeux dans les réseaux", November 29,

- Peter Marbach from University of Toronto, Canada talking on "Rate Control and Medium Access Control in Wireless Networks", October 26,
- Avi Berman from Technion, Israel talking on "On the second eigenvalues of matrices associated with TCP", October 24,
- Gonzalo Perera from Universidad de la Republica, Montevideo talking on "Quelques résultats sur l'analyse statistiques des performances", September 23.
- Venkat Anantharam from EECS University of California, Berkeley talking on
  - "Queueing theory and networking for hyper-caffeinated customers", October 13,
  - "The reliability of communicating via timing the arrivals to a FIFO queue", September 29,
  - "A Game theoretic look at the Gaussian multiaccess channel", September 23,
- Renata Teixeira from University of California, San Diego, California, USA talking on "Network Sensitivity to Intradomain Routing Changes", May 31,
- E. Coffman from Columbia University, NY, USA talking on "Self Assembly Processes in Nanoscience" April 29,
- Harold Kushner from Brown University, on "Scheduling and Control of Multi-Node Mobile Communications Systems with Randomly-Varying Channels by Stability Methods", April 19,
- Armand Makowski from Univesity of Maryland, USA, talking on
  - "The output of a cache under the independent reference model – Where did the locality of reference go?" , February 15,
  - "Locality of reference in streams of requests: Modeling temporal correlations via stochastic orderings" , February 16.

9.1.3. Miscellaneous

- TREC animates the project-team seminar: http://www.di.ens.fr/~trec/trec-eng.html
- K.B. Kim animated the project-team reading group.
- B. Błaszczyszyn maintains a web-page on stochastic geometry for communications http://www.di.ens.fr/~trec/sg
- 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 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 of 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) of F. Baccelli, T. Bonald, A. Proutière, B. Radunovic and M.A. Tran on Communication Networks (48H).
- Undergraduate course (master level) of F. Baccelli, P. Brémaud, J.F. Le Gall and C. Bordenave on applied probability (48h).

Eurandom Course on spatial stochastic models by F. Baccelli, within the framework of the Eurandom Chair, from October 2004 to May 2005.

Universiy of Ottawa Course on measure theoretic probability by D. McDonald (39h) from September to December 2004.

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 M. Jonkheere (Ecole Polytechnique, December 9), E. Roy (Paris 6, December 9), L. Viennot (HDR Paris 7, November 28), D. Raffo (Paris 6, September 15), O. Dousse (EPFL, July 12), P. Moyal (ENST, July 11), M. Lelarge (Ecole Polytechnique, February) and M. Draief (Paris 7, January 24).
- Co-organizer of the first workshop on Spatial Stochastic Modeling of Wireless Networks (SpaSWiN 2005; http://www.spaswin.org/), in conjunction with WiOpt 2005 (http://www.wiopt.org/wiopt05/).
- Co-organizer of the invited session on Stochastic Geometry and Telecommunication Modeling organized during the 25th European Meeting of Statisticians (EMS’05); July 24–28, Olso, Norway, (http://www.ems2005.no/).
- Member of the evaluation committee of the Metropolis RNRT project and of the hiring committee of Université de Louvain.
- Member of the program committee of the following conferences: Infocom 05 and 06, Sigmetrics 05 and 06, WiOpt 06, FAWN 2006,
- Presentations at the following conferences:

  * EuroNGI Workshop on QoS and Traffic Control, December 7–9,
  * IFIP WG7.3 Workshop, Juan les Pins, October 8,
  * Bern Conference on Stochastic Geometry, October 3–7 (invited lecture),

  * IMA Conference on the mathematics of wireless networks, Minneapolis, June 27–July 1 (invited lecture),
  * Hyke conference, Rome, April 14–15 (invited lecture),
  * Infocom 05, Miami, April 13–17,
  * Freudenstadt Conference on Stochastic Geometry, February 28 – March 2 (invited lecture),
  * QoSIP, Catania, Italy, February 2–4 (plenary lecture),
  * Workshop on Internet Measurement, Modeling and Analysis, Seoul, Korea, January 10–12,
  * First Franco Nordic Congress of Mathematics, Reykjavik, Iceland, January 6–8.

– Presentations at the following seminars:

  * Colloquium of Ecole Polytechnique, Palaiseau, November 8,
  * Microsoft MSR Cambridge, UK, September 1,
  * MIT, Boston, USA, March 14,
  * KAIST, Daejeon, Korea, January 14.

B. Błaszczyszyn

– Co-organizer of the first workshop on Spatial Stochastic Modeling of Wireless Networks (SpaSWiN 2005; http://www.spaswin.org/) in conjunction with WiOpt 2005 (http://www.wiopt.org/wiopt05/).
– Organizer of the invited session on Spatial Stochastic Modeling of Communication Networks during 13th Informs Applied Probability Conference, Ottawa, Canada, July 2005 (http://appliedprob.society.informs.org/ottawaconf.html),
– Co-organizer of the invited session on Stochastic Geometry and Telecommunication Modeling organized during the 25th European Meeting of Statisticians (EMS'05); July 24–28, Olso, Norway (http://www.ems2005.no/).
– Tutorial entitled "Stochastic Geometry and Wireless Networks", Performance, Juan-les-Pins, France, October 2005 (http://www-sop.inria.fr/maestro/performance2005/).
– Presentations at the following conferences:

  * Workshop on Stochastic Geometry and Spatial Statistics, Freudenstadt, Germany, February-March 2005; (http://mspcdip.mathematik.uni-karlsruhe.de/english/personen/Freudenstadt05/Freudenstadt.html),
  * IEEE Infocom, Miami, FL. USA, March 2005 (http://www.ieee-infocom.org/2005),
  * 13th Informs Applied Probability Conference, Ottawa, Canada, July 2005 (http://appliedprob.society.informs.org/ottawaconf.html),
  * 25th European Meeting of Statisticians, Oslo, Norway, July 2005 (http://www.ems2005.no/).

T. Bonald

- Member of the program committee of Performance 2005 (http://www-sop.inria.fr/maestro/performance2005/), Sigmetrics 2005 (http://www.cse.cuhk.edu.hk/~sigm2005/), Sigmetrics/Performance 2006 (http://www.cs.wm.edu/sigm06/), RAWNET 2006 (http://rawnet.org/).
- Poster chair of Performance 2005.
- Tutorial chair of Sigmetrics/Performance 2006 (http://www.cs.wm.edu/sigm06/).
- Tutorial entitled "A teletraffic theory for the Internet" with Alexandre Proutière, Performance, Juan-les-Pins, France, October 2005 (http://www-sop.inria.fr/maestro/performance2005/).
- Presentations at the following conferences:
  * RAWNET, Riva del Guarda, Italy, April 2005 (http://www.wiopt.org/wiopt05/workshops.html),
  * ITC, Beijing, China, August 2005 (http://www.itc19.org/itc/),
  * Performance, Juan-les-Pins, France, October 2005 (http://www-sop.inria.fr/maestro/performance2005/),
- Invited talk at the University of Maryland, May 2005.

Ch. Bordenave

- Presentation at the following conferences:
  * SpaSWiN, Riva del Garda, Italy, April 2005 (http://www.spaswin.org/),
  * 25th European meeting of statisticians, Oslo, Norway, July 2005 (http://www.ems2005.no/),
  * 43th Allerton Conference on communication, control and computing, Monticello, IL, USA, September 2005 (http://www.csl.uiuc.edu/allerton/).
- Participation at Winter School on Probabilistic Methods in High Dimension Phenomena, Toulouse, France 2005 (http://www.lsp.ups-tlse.fr/Proba_Winter_School/).
- Presentation at the following seminars:
  * Heriot Watt University, September 2005,
  * University College Cork, October 2005.

P. Brémaud

- Invited lecture at the 27th Finnish Summer School in Probability Theory, June 6–10 2005, Abo University, Turku, Finland (http://www.abo.fi/fak/mnf/mate/abo05/),
- Invited lecture at the 1st Franco-Nordic Congress of Mathematicians, January 6–9 2005, Reykjavik, Island. (http://www.raunvis.hi.is/24NordicCongress/).

A. Chaintreau

- Presentation at the following conferences:
  * SpaSWiN'05, Riva del Guarda, Italy, April 2005 (http://www.spaswin.org/),
  * Cornell Probability Summer School, Ithaca, NY, USA, July, 2005 (http://www.math.cornell.edu/~lawler/sum2005.html),
  * Co-Next, Toulouse, France, October 2005,

- Participations at the following conferences:
  - IEEE Infocom, Miami, FL, USA, March 2005 (http://www.ieee-infocom.org/2005),
  - ACM Sigcomm, Philadelphia, PA, USA, August 2005 (http://www.acm.org/sigcomm/sigcomm2005/).
  - Winter School on Probabilistic Methods in High Dimension Phenomena, Toulouse, France 2005 (http://www.lsp.ups-tlse.fr/Proba_Winter_School/).
- Presentation at the following seminars:
  - Cambridge statistical laboratory, February 2005,
  - Cambridge University Computer Lab, February and August 2005.

K.-B. Kim

- Presentation at IEEE Infocom, Miami, FL, USA, March 2005 (http://www.ieee-infocom.org/2005).

M. Lelarge

- Participation at Cornell Probability Summer School, Ithaca, NY, USA, July, 2005 (http://www.math.cornell.edu/~lawler/sum2005.html).
- Presentations at the following conferences:
  - 13th Informs Conference, Ottawa, Canada, July 2005 (http://appliedprob.society.informs.org/ottawaconf.htm
  - EURANDOM/EuroNGI, Workshop on Rare events in communication networks, Eindhoven, The Netherlands, February 2005 http://www.eurandom.tue.nl/.
- Presentation at the following seminars:
  - University College Cork, Ireland, September 2005,
  - Hamilton Institute, Ireland, November 2005.

D. McDonald

- Local organizer and member of the program committee of the 13th Informs Applied Probability Conference, July 2005 in Ottawa Canada (http://appliedprob.society.informs.org/ottawaconf.html).
- Organizer of Fields Institute Summer School and Workshop on rare events, June–July 2005 in Ottawa Canada (http://www.fields.utoronto.ca/programs/scientific/05-06/rare_events/).
- Presentations at the following conferences:
  - First EuroNGI Conference, Roma, April 2005 (http://eurongi.enst.fr/p_en_Events_Events2005_Conference_
  - Informs Applied Probability Conference, Ottawa, Canada, July 2005 (http://appliedprob.society.informs.org/ottawaconf.html).
- Presentation at the seminar in Weierstrasse Institute, Berlin, May 2005.

A. Proutière

- Member of the program committee of IEEE Infocom 2005 (http://www.ieee-infocom.org/2005) and 2006 (http://www.ieee-infocom.org/2006).

- Co-chair of RAWNET 2005 and 2006, the first and second workshops on resource allocation in wireless networks (http://rawnet.org/), in conjunction with the WiOpt conference (http://www.wiopt.org/).
- Tutorial entitled “A teletraffic theory for the Internet” with Thomas Bonald, Performance, Juan-les-Pins, France, October 2005 (http://www-sop.inria.fr/maestro/performance2005/).
- Presentation at the following conferences:
  * European Wireless, Nicosia, Cyprus, April 2005 (http://www.european-wireless2005.de),
  * 43th Allerton Conference on communication, control and computing, Monticello, IL, USA, September 2005 (http://www.csl.uiuc.edu/allerton/),
  * EuroNGI Workshop on QoS and Traffic Control, Paris, France, December 2005 (http://perso.rd.francetelecom.fr/roberts/EuroNGIQoS/).

J. Reynier

- Lecture at the ENST Romanian market for Dacia Logan, March 2005.
- Lecture at CGTI (Conseil Général des Technologies de l’Information), June 2005.
- seminar at the University of Ottawa, Canada, November 2005.

E. Roy

- was visiting the Mathematical Department of the Nicolaus Copernicus University, Toruń, Poland, in April 2005 as visiting scientist.
- Presentation at the following seminars:
  * Séminaire d’analyse et de probabilité Brest, France,
  * Séminaire de théorie ergodique et de probabilité, Tours, France,
  * Séminaire du laboratoire de mathématiques Raphaël Salem, Rouen, France,
  * Ergodic theory seminar, Toruń, Poland,
  * Probability seminar, Toruń, Poland.

10. Bibliography

Major publications by the team in recent years

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[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.

Doctoral dissertations and Habilitation theses

[4] M. JONKHEERE. *Partage de charge et allocation de capacité insensible dans les réseaux de télécommunications*, Ph. D. Thesis, Ecole polytechnique, 2005.

[5] M. LELARGE. *Rare events in networks*, Ph. D. Thesis, Ecole polytechnique, 2005.

[6] E. ROY. *Mesures de Poisson, infinie divisibilité et propriétés ergodiques*, Ph. D. Thesis, Laboratoire de Probabilités, Paris 6, 2005.

Articles in refereed journals and book chapters

[7] F. BACCELLI, S. FOSS, M. LELARGE. *Tails in generalized Jackson networks with subexponential service-time distributions*, in "J. Appl. Probab.", see also INRIA RR 5081, vol. 42, n° 2, 2005, p. 513–530, http://www.inria.fr/rrrt/rr-5081.html.

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[10] P. BRÉMAUD, L. MASSOULIÉ, A. RIDOLFI. *Power spectra of random spike fields and related processes*, in "Adv. Appl. Probab.", vol. 38, n° 4, 2005.

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

[13] R. FOLEY, D. MCDONALD. *Bridges and Networks: Exact Asymptotics*, in "Ann. Appl. Probab.", vol. 15, 2005, p. 542–586.

[14] R. FOLEY, D. MCDONALD. *Large Deviations of a Modified Jackson Network: Stability and Rough Asymptotics*, in "Ann. Appl. Probab.", vol. 15, 2005, p. 519–541.

[15] M. LELARGE. *Fluid limit of generalized Jackson queueing networks with stationary and ergodic arrivals and service times*, in "J. Appl. Probab.", see also INRIA RR 5069, vol. 42, nº 2, 2005, p. 491–512, http://www.inria.fr/rrrt/rr-5069.html.

Publications in Conferences and Workshops

[16] F. BACCELLI, C. BORDENAVE. *The Radial Spanning Tree of a Poisson Point Process*, in "Proceedings of 43th Allerton Conference, Illinois", submitted to Annals of Applied Probab., Illinois University at Urbana Champaign, September 2005.

[17] 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://www.inria.fr/rrrt/rr-5517.html.

[18] F. BACCELLI, A. CHAINTREAU, Z. LIU, A. RIABOV. *The One-to-Many TCP Overlay: A Scalable and Reliable Multicast Architecture*, in "Proceedings of IEEE Infocom, Miami, FL, USA", March 2005.

[19] F. BACCELLI, K.-B. KIM, D. DE VLEESCHAUWER. *Analysis of the Competition between Wired, DSL and Wireless Users in an Access Network'*, in "Proceedings of IEEE Infocom, Miami, FL, USA", see also INRIA RR 5306, March 2005, http://www.inria.fr/rrrt/rr-5306.html.

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

[21] T. BONALD, A. PROUTIERE. *Conservative Estimates of Blocking and Outage Probabilities in CDMA Networks*, in "Proceedings of Performance, Juan-les-Pins, France", IFIP, September 2005.

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[28] F. BACCELLI, C. BORDENAVE. *The Radial Spanning Tree of a Poisson Point Process*, RR, nº 5707, INRIA, Rocquencourt, September 2005, http://www.inria.fr/rrrt/rr-5707.html.

[29] F. BACCELLI, B. BŁASZCZYSZYN, M. K. KARRAY. *Blocking Rates in Large CDMA Networks via a Spatial Erlang Formula*, appeared in Proc. of IEEE Infocom'05, RR, nº 5517, INRIA, Rocquencourt, March 2005, http://www.inria.fr/rrrt/rr-5517.html.

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