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Activity Report 2012

Project-Team TREC

Theory of networks and communications

IN COLLABORATION WITH: Département d'Informatique de l'Ecole Normale Supérieure

RESEARCH CENTER
Paris - Rocquencourt

THEME
Networks and Telecommunications

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Project-Team TREC

Keywords: Wireless Networks, Network Dynamics, Stochastic Geometry, Random Graphs, Analysis Of Algorithms

Creation of the Project-Team: 2001 January 01, end of the Project-Team: 2012 December 31.

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2. Overall Objectives

2.1. Introduction

TREC is a joint Inria-ENS project-team. It is focused on the modeling, the control and the design of communication networks and protocols. Its methodological activities are combined with projects defined with industrial partners, notably Alcatel-Lucent, Technicolor, Qualcomm and Orange. The main research directions are:

- modeling and performance analysis of wireless networks: network information theory, coverage and load analysis, power control, evaluation and optimization of the transport capacity, self organization;
- stochastic network dynamics: stability, worst-case performance analysis using the (max,plus) algebra, network calculus, perfect simulation, inverse problems, distributed consensus;
- economics of networks: epidemic risk model, incentives, security, insurance, diffusion of innovations;
- the development of mathematical tools based on stochastic geometry, random geometric graphs and spatial point processes: Voronoi tessellations, coverage processes, random spatial trees, random fields, percolation;
- combinatorial optimization and analysis of algorithms: random graphs, belief propagation.

TREC's web site at Inria http://www.inria.fr/equipes/trec and ENS http://www.di.ens.fr/~trec.

2.2. Highlights of the Year

F. Baccelli was awarded the Simons Math+X Chair to further develop Wireless Stochastic Geometry.

M. Lelarge was the recipient of the 2012 ACM SIGMETRICS Rising Star Researcher Award. http://www.sigmetrics.org/risingstar-2012.shtml

3. Research Program

3.1. Research Program

- **Modeling and performance analysis of wireless networks.** Our main focus was on cellular networks, mobile ad hoc networks (MANETs) and their vehicular variants called VANETs.

  Our main advances about wireless networks have been based on the development of analytical tools for their performance analysis and on new results from network information theory.

  Concerning cellular networks, the main questions bear on coverage and capacity in large CDMA networks when taking intercell interferences and power control into account. Our main focus has been on the design of: 1) a strategy for the densification and parameterization of UMTS and future OFDM networks that is optimized for both voice and data traffic; 2) new self organization and self optimization protocols for cellular networks e.g. for power control, sub-carrier selection, load balancing, etc.

  Concerning MANETs, we investigated MAC layer scheduling algorithms, routing algorithms and power control. The MAC protocols we considered are based on Aloha and CSMA as well as their cognitive radio extensions. We investigated opportunistic routing schemes for MANETs and VANETs. The focus was on cross layer optimizations allowing one to maximize the transport capacity of multihop networks.

- **Theory of network dynamics.** TREC is pursuing the analysis of network dynamics by algebraic methods. The mathematical tools are those of discrete event dynamical systems: semi-rings, and in particular network calculus, ergodic theory, perfect simulation, stochastic comparison, inverse problems, large deviations, etc. Network calculus gives results on worst-case performance evaluation; ergodic theory is used to assess the stability of discrete event dynamical systems; inverse problem methods are used to estimate some network parameters from external observations and to design network probing strategies.
- **The development of stochastic geometry and random geometric graphs tools.** Stochastic geometry is a rich branch of applied probability which allows one to quantify random phenomena on the plane or in higher dimension. It is intrinsically related to the theory of point processes and also to random geometric graphs. Our research is centered on the development of a methodology for the analysis, the synthesis, the optimization and the comparison of architectures and protocols to be used in wireless communication networks. The main strength of this method is its capacity for taking into account the specific properties of wireless links, as well as the fundamental question of scalability.
- **Combinatorial optimization and analysis of algorithms.** In this research direction started in 2007, we build upon our expertise on random trees and graphs and our collaboration with D. Aldous in Berkeley. Sparse graph structures have proved useful in a number of applications from information processing tasks to the modeling of social networks. We obtained new results in this research direction: computation of the asymptotic for the rank of the adjacency matrix of random graphs, computation of the matching number and the b-matching number of large graphs. We also applied our result to design bipartite graph structures for efficient balancing of heterogeneous loads and to analyze the flooding time in random graphs.
- **Economics of networks** The premise of this relatively new direction of research, developed jointly with Jean Bolot [SPRINT ATL and then TECHNICOLOR] is that economic incentives drive the development and deployment of technology. Such incentives exist if there is a market where suppliers and buyers can meet. In today's Internet, such a market is missing. We started by looking at the general problem of security on Internet from an economic perspective.

4. Application Domains

4.1. Application Domains

We have investigated various applications of our research results with the following industrial partners and user associations:

- **Wireless Networks**
  - Alcatel-Lucent Bell Laboratories (L. Thomas and L. Roullet) on self optimization in cellular networks.
  - Qualcomm (T. Richardson and his group) on improvements of CSMA CA.
  - Orange (M. Karray) on cellular networks.
- **Network Dynamics**
  - Thalès and Real-Time-at-Work on embedded networks.
  - Grenouille on probing in access networks.
- **Networks Economics**
  - Technicolor (J. Bolot) on economic incentives.

5. Software and Platforms

5.1. Gibbs' Sampler

Participants: François Baccelli, Chung Shue Chen.

The work on the self optimization of cellular networks based on Gibbs' sampler (see Section 6.1.1.5) carried out wit Chung Shue Chen (ALU) in the joint laboratory with Alcatel-Lucent, led to the development of a software prototype that was presented by L. Roullet at the Inria Alcatel-Lucent joint laboratory seminar in November 2012.

5.2. PSI2

Participant: Ana Bušić.

The work on perfect sampling (see Section 6.2.2) has been partially implemented in a software tool PSI2, in collaboration with MESCAL team [Inria Grenoble - Rhône-Alpes]; https://gforge.inria.fr/projects/psi.

6. New Results

6.1. Design and Performance Analysis of Wireless Networks

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Chung Shue Chen, Miodrag Jovanović, Holger Paul Keeler, Mir Omid Haji Mirsadeghi, Frédéric Morlot, Tien Viet Nguyen.

CDMA/UMTS, Wireless LANs, ad hoc networks, IEEE 802.11, mesh networks, cognitive radio, Hiperlan, CSMA, TCP, MAC protocols, exponential back-off protocols, signal to interference ratio, coverage, capacity, transport capacity, admission and congestion control.

This axis bears on the analysis and the design of wireless access communication networks. Our contributions are organized in terms of network classes: cellular networks, wireless LANs and MANETs, VANETs. We also have a section on generic results that regard more general wireless networks. 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, distributed control algorithms, self organization protocols.

6.1.1. Cellular Networks

The activity on cellular networks has several complementary facets ranging from performance evaluation to protocol design. The work is mainly based on strong collaborations with Alcatel-Lucent and Orange Labs.

6.1.1.1. Effect of Opportunistic Scheduling on the Quality of Service Perceived by the Users in OFDMA Cellular Networks

Our objective in [17] is to analyze the impact of fading and opportunistic scheduling on the quality of service perceived by the users in an Orthogonal Frequency Division Multiple Access (OFDMA) cellular network. To this end, assuming Markovian arrivals and departures of customers that transmit some given data volumes, as well as some temporal channel variability (fading), we study the mean throughput that the network offers to users in the long run of the system. Explicit formulas are obtained in the case of allocation policies, which may or may-not take advantage of the fading, called respectively opportunistic and non-opportunistic. The main practical results of the present work are the following. Firstly we evaluate for the non-opportunist allocation the degradation due to fading compared to Additive White Gaussian Noise (AWGN) (that is, a decrease of at least 13% of the throughput). Secondly, we evaluate the gain induced by the opportunistic allocation. In particular, when the traffic demand per cell exceeds some value (about 2 Mbits/s in our numerical example), the gain induced by opportunism compensates the degradation induced by fading compared to AWGN. Partial results were presented at ComNet in 2009 [61].

6.1.1.2. Impact of propagation-loss model on the geometry and performance of cellular networks

6.1.1.2.1. Impact of Shadowing on QoS

Shadowing is believed to degrade the quality of service in wireless cellular networks. In [18] we discovered a more subtle reality. Increasing variance of the lognormal shadowing tends to “separate” the strongest (serving BS) signal from all other signals — a phenomenon observed for heavy-tailed distributions and called “single big jump principle”. In consequence, in some cases, an increase of the variance of the shadowing can significantly reduce the mean interference factor and improve some QoS metrics in interference limited systems. We exemplify this phenomenon, similar to stochastic resonance and related to the “single big jump principle” of the heavy-tailed log-nornal distribution, studying the blocking probability in regular, hexagonal networks in a semi-analytic manner, using a spatial version of the Erlang’s loss formula combined with Kaufman-Roberts algorithm.

6.1.1.2.2. Using Poisson processes to model lattice cellular networks

In [51] we mathematically proved that a large spatially homogeneous (arbitrary, including hexagonal) network is perceived by a typical user as an equivalent (infinite) Poisson network, provided shadowing is strong enough. This justifies an almost ubiquitous Poisson assumption made in the stochastic-analytic approach to study of the quality of user-service in cellular networks.

6.1.1.2.3. Linear-Regression Estimation of the Propagation-Loss Parameters Using Mobiles’ Measurements

In [35] we proposed a new linear-regression model for the estimation of the path-loss exponent and the parameters of the shadowing from the propagation-loss data collected by the mobiles with respect to their serving base stations. The model is based on the aforementioned Poisson convergence result.

6.1.1.3. Quality of Real-Time Streaming in Wireless Cellular Networks

In [50] we present a new stochastic service model with service capacity sharing and interruptions, meant to be useful for the performance evaluation and dimensioning of wireless cellular networks offering real-time streaming, like e.g. mobile TV. Our general model takes into account Markovian, multi-class process of call arrivals, arbitrary streaming time distribution, and allows for a general service (outage) policy saying which users are temporarily denied the service due to insufficient service capacity. Using Palm theory formalism, we develop expressions for several important characteristics of this model, including mean time spent in outage and mean number of outage incidents for a typical user of a given class. We also propose some natural class of least-effort-served-first service policies, for which the aforementioned expressions can be efficiently evaluated on the basis of the Fourier analysis of Poisson process. Last but not least, we show how our model can be used to analyse the quality of real-time streaming in 3GPP Long Term Evolution (LTE) cellular networks. We identify and evaluate an optimal and a fair service policy, the latter being suggested by LTE implementations, as well as propose some intermediate policies which allow to solve the optimality/fairness trade-off caused by unequal user radio-channel conditions.

6.1.1.4. Theoretically Feasible QoS in a MIMO Cellular Network Compared to the Practical LTE Performance

Our goal in [39] is to build a global analytical approach for the evaluation of the quality of service perceived by the users in wireless cellular networks which is calibrated in some reference cases. To do so, a model accounting for interference in a MIMO cellular system is firstly described. An explicit expression of users bit-rates theoretically feasible from the information theory point of view is then deduced. The comparison between these bit-rates and practical LTE performance permits to obtain the progress margins for potential evolution of the technology. Moreover, it leads to an analytical approximate expression of the system performance which is calibrated with the practical one. This expression is the keystone of a global analytical approach for the evaluation of the QoS perceived by the users in the long run of users arrivals and departures in the network. We illustrate our approach by calculating the users QoS as function of the cell radius in different mobility and interference cancellation scenarios.

6.1.1.5. Self-Optimization of Radio Resources in Cellular Networks

In [19], we surveyed the mathematical and algorithmic tools for the self-optimization of mobile cellular networks based on Gibbs' sampler. This technique allows for the joint optimization of radio resources in heterogeneous cellular networks made of a juxtaposition of macro and small cells. It can be implemented in a distributed way and nevertheless achieves minimal system-wide potential delay. Results show that it is effective in both throughput and energy efficiency.

Three patents were filed on this line of thought under the Inria/Alcatel–Lucent joint laboratory.

6.1.1.6. Coverage in Cellular Networks

Cellular networks are in a major transition from a carefully planned set of large tower-mounted base-stations (BSs) to an irregular deployment of heterogeneous infrastructure elements that often additionally includes micro, pico, and femtocells, as well as distributed antennas. In a collaboration with H. Dhillon, J. Andrews and R. Ganti [UT Austin, USA] [20], we developed a model for a downlink heterogeneous cellular network (HCN) consisting of K tiers of randomly located BSs, where each tier may differ in terms of average transmit power, supported data rate and BS density. Assuming a mobile user connects to the strongest candidate BS, the resulting Signal-to-Interference-plus-Noise-Ratio (SINR) is greater than 1 when in coverage, Rayleigh fading, we derived an expression for the probability of coverage (equivalently outage) over the entire network under both open and closed access. One interesting observation for interference-limited open access networks is that at a given SINR, adding more tiers and/or BSs neither increases nor decreases the probability of coverage or outage when all the tiers have the same SINR threshold.

6.1.2. Mobile Ad Hoc Networks

A 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. This year, we worked on a game theoretic view of Spatial Aloha in collaboration with E. Altman and M.K. Hanawal [Inria MAESTRO] [22] This line of though is currently continued with Chandramani Singh. We also compared the performance of spatial Aloha to CSMA.

6.1.2.1. Improvement of CSMA/CA's Spatial Reuse

The most popular medium access mechanism for such ad hoc networks is CSMA/CA with RTS/CTS. In CSMA-like mechanisms, spatial reuse is achieved by implementing energy based guard zones. In a collaboration with Qualcomm [12], we considered the problem of simultaneously scheduling the maximum number of links that can achieve a given signal to interference ratio (SIR). Using tools from stochastic geometry, we studied and maximized the medium access probability of a typical link. Our contributions are two-fold: (i) We showed that a simple modification to the RTS/CTS mechanism, viz., changing the receiver yield decision from an energy-level guard zone to an SIR guard zone, leads to performance gains; and (ii) We showed that this combined with a simple modification to the transmit power level – setting it to be inversely proportional to the square root of the link gain – leads to significant improvements in network throughput. Further, this simple power-level choice is no worse than a factor of two away from optimal over the class of all "local" power level selection strategies for fading channels, and further is optimal in the non-fading case. The analysis relies on an extension of the Matérn hard core point process which allows us to quantify both these SIR guard zones and this power control mechanism.

6.1.2.2. Comparison of the maximal spatial throughput of Aloha and CSMA in Wireless multihop Ad-Hoc Networks

In [46] this paper we compare the spatial throughput of Aloha and Carrier Sense Multiple Access (CSMA) in Wireless multihop Ad-Hoc Networks. In other words we evaluate the gain offered by carrier sensing (CSMA) over the pure statiscal collision avoidance which is the basis of Aloha. We use a Signal-to-Interference-and-Noise Ratio (SINR) model where a transmission is assumed to be successful when the SINR is larger than a given threshold. Regarding channel conditions, we consider both standard Rayleigh and negligible fading. For slotted and non-slotted Aloha, we use analytical models as well as simulations to study the density of successful transmissions in the network. As it is very difficult to build precise models for CSMA, we use only simulations to compute the performances of this protocol. We compare the two Aloha versions and CSMA on a fair basis, i.e. when they are optimized to maximize the density of successful transmissions. For slotted Aloha, the key optimization parameter is the medium access probability, for non-slotted Aloha we tune the mean back-off time, whereas for CSMA it is the carrier sense threshold that is adjusted. Our study shows that CSMA always outperforms slotted Aloha, which in turn outperforms its non-slotted version.

6.1.2.3. Stochastic Analytic Evaluation of End-to-End Performance of Linear Nearest Neighbour Routing in MANETs with Aloha

Planar Poisson models with the Aloha medium access scheme have already proved to be very useful in studies of mobile ad-hoc networks (MANETs). However, it seems difficult to quantitatively study the performances of end-to-end routing in these models. In order to tackle this problem, in [52], we study a linear stationary route embedded in an independent planar field of interfering nodes. We consider this route as an idealization of a "typical" route in a MANET obtained by some routing mechanism. Such a decoupling allows us to obtain many numerically tractable expressions for local and mean end-to-end delays and the speed of packet progression, assuming slotted Aloha MAC and the Signal-to-Interference-and-Noise Ratio (SINR) capture condition, with the usual power-law path loss model and Rayleigh fading. These expressions show how the network performance depends on the tuning of Aloha and routing parameters and on the external noise level. In particular we show a need for a well-tuned lattice structure of fixed relaying nodes, which helps to relay packets on long random routes in the presence of a non-negligible noise. We also consider a Poisson-line MANET model, in which nodes are located on roads forming a Poisson-line process. In this case our linear route is rigorously (in the sense of Palm theory) the typical route in this Poisson-line MANET.

6.1.3. Vehicular Ad-Hoc Networks (VANETs)

Vehicular Ad Hoc NETworks (VANETs) are special cases of MANETs where the network is formed between vehicles. VANETs are today the most promising civilian application for MANETs and they are likely to revolutionize our traveling habits by increasing safety on the road while providing value added services.

6.1.3.1. Point-to-Point, Emergency and Broadcast Communications

Our aim in [36] is to analyze the Aloha medium access (MAC) scheme in one-dimensional, linear networks, which might be an appropriate assumption for VANETs. The locations of the vehicles are assumed to follow a homegeneous Poisson point process. Assuming powerlaw mean path-loss and independent point-to-point fading we study performance metrics based on the signal-over-interference and noise ratio (SINR). In contrast to previous studies where the receivers are at a fixed distance from the transmitter, we assume here that the receivers are the nearest neighbors of the transmitters in the Poisson process and in a given direction. We derive closed formulas for the capture probability and for the density of progress of a packet sent by a given node. We compute the mean delay to send a packet transmitted at each slot until successful reception. We also evaluate an upper bound to discover the neighborhood within a given space interval. We show that we can include noise in the previous models.

6.1.4. Cognitive Radio Networks

We wrote a survey [26] on the probabilistic framework which can be used to model and analyze cognitive radio networks using various classes of MAC protocols (including carrier sensing based multiple access schemes and Aloha schemes). For each model, analytical results were derived for important performance metrics. This leads to a quantification of the interplay between primary and secondary users in such networks.

6.2. Network Dynamics

Participants: Abir Benabid, Julieta Bollati, Anne Bouillard, Ana Bušić, Emilie Coupechoux, Nadir Farhi.

Queueing network, stability, inversion formula, probing, estimator, product-form, insensitivity, markov decision, max-plus algebra, network calculus.

6.2.1. Network Calculus

Network calculus is a theory that aims at computing deterministic performance guarantees in communication networks. This theory is based on the (min,plus) algebra. Flows are modeled by an *arrival curve* that upper-bounds the amount of data that can arrive during any interval, and network elements are modeled by a *service curve* that gives a lower bound on the amount of service offered to the flows crossing that element. Worst-case performances are then derived by combining these curves.

6.2.1.1. Performance bounds in FIFO tandem networks

In cooperation with Giovanni Stea [University of Pisa, Italy], we present in [31] algorithms to compute worst-case performance upper bounds when the service policy is FIFO, using linear programming. Linear programming leads to tight bounds; however, the computation corst is too high for reasonable-size networks. We then develop approximate solution schemes to find both upper and lower delay bounds on the worst-case delay. Both of them only require to solve just one LP problem, and they produce bounds which are generally more accurate than those found in the literature. Finally, we have a conjecture on what sould be the worst-case trajectory under usual assumptions.

6.2.1.2. Feed-forward networks with wormhole routing discipline

In collaboration with Bruno Gaujal [Inria Rhone Alpes] and Nadir Farhi [IFFSTAR] we are working on a model of performance bound calculus on feed-forward networks where data packets are routed under wormhole routing discipline. We are interested in determining maximum end-to-end delays and backlogs for packets going from a source node to a destination node, through a given virtual path in the network. Our objective is to give a "network calculus" approach to calculate the performance bounds. For this, we propose a new concept of curves that we call *packet curves*. The curves permit to model constraints on packet lengths for data flows, when the lengths are allowed to be different. We used this new concept to propose an approach for calculating residual services for data flows served under non preemptive service disciplines. This notion also enabled us to differentiate different classes of service policies: those that are based on a packet count (like round-robin and its generalized version), where the packet curve will be useful to tighten the bounds computed, and those that are based on the amount of data served (FIFO, priorities), where it won't be useful. These results have been presented at Valuetools (invited paper, [29]).

6.2.1.3. Using arrival curves for detecting anomalies in a network

In cooperation with Aurore Junier [Inria/IRISA] and Benoît Ronot [Alcatel-Lucent], we present an on-line algorithm that performs a flow of messages analysis. More precisely, it is able to highlight hidden abnormal behaviors that existing network management methods would not detect. Our algorithm uses the notion of constraint curves, introduced in the Network Calculus theory, defining successive time windows that bound the flow. The advantage of this algorithm is that it can be performed online, and in a second version has different levels of precision. This work has been presented in [30] and a patent [57] has been submitted.

6.2.1.4. Min,plus algorithms for fast weak-KAM integrators

In cooperation with Erwan Faou [IPSO-Inria Rennes, DMA-ENS] and Maxime Zavidovique [Paris 6]. We consider a numerical scheme for Hamilton-Jacobi equations based on a direct discretization of the Lax-Oleinik semi-group. We prove that this method is convergent with respect to the time and space stepsizes provided the solution is Lipschitz, and give an error estimate. Moreover, we prove that the numerical scheme is a geometric integrator satisfying a discrete weak-KAM theorem which allows to control its long time behavior. Taking advantage of a fast algorithm for computing min-plus convolutions based on the decomposition of the function into concave and convex parts, we show that the numerical scheme can be implemented in a very efficient way. The results can be found in [49].

6.2.2. Perfect Sampling of Queueing Systems

Propp and Wilson introduced in 1996 a perfect sampling algorithm that uses coupling arguments to give an unbiased sample from the stationary distribution of a Markov chain on a finite state space $\mathcal{X}$. In the general case, the algorithm starts trajectories from all $x \in \mathcal{X}$ at some time in the past until time $t = 0$. If the final state is the same for all trajectories, then the chain has coupled and the final state has the stationary distribution of the Markov chain. Otherwise, the simulations are started further in the past. This technique is very efficient if all the events in the system have appropriate monotonicity properties. However, in the general (non-monotone) case, this technique requires that one consider the whole state space, which limits its application only to chains with a state space of small cardinality.

6.2.2.1. Piecewise Homogeneous Events

In collaboration with Bruno Gaujal [Inria Grenoble - Rhone-Alpes], we proposed in [15] a new approach for the general case that only needs to consider two trajectories. Instead of the original chain, we used two bounding processes (envelopes) and we showed that, whenever they couple, one obtains a sample under the stationary distribution of the original chain. We showed that this new approach is particularly effective when the state space can be partitioned into pieces where envelopes can be easily computed. We further showed that most Markovian queueing networks have this property and we propose efficient algorithms for some of them.

The envelope technique has been implemented in a software tool PSI2 (see Section 5.2).

6.2.2.2. Perfect Sampling of Networks with Finite and Infinite Capacity Queues

In [33], we consider open Jackson queueing networks with mixed finite and infinite buffers and analyze the efficiency of sampling from their exact stationary distribution. We show that perfect sampling is possible, although the underlying Markov chain has a large or even infinite state space. The main idea is to use a Jackson network with infinite buffers (that has a product form stationary distribution) to bound the number of initial conditions to be considered in the coupling from the past scheme. We also provide bounds on the sampling time of this new perfect sampling algorithm under hyper-stability conditions (to be defined in the paper) for each queue. These bounds show that the new algorithm is considerably more efficient than existing perfect samplers even in the case where all queues are finite. We illustrate this efficiency through numerical experiments.

6.2.3. Markov Chains and Markov Decision Processes

Solving Markov chains is in general difficult if the state space of the chain is very large (or infinite) and lacking a simple repeating structure. One alternative to solving such chains is to construct models that are simple to analyze and provide bounds for a reward function of interest. The bounds can be established by using different qualitative properties, such as stochastic monotonicity, convexity, submodularity, etc. In the case of Markov decision processes, similar properties can be used to show that the optimal policy has some desired structure (e.g. the critical level policies).

6.2.3.1. Stochastic Monotonicity

In collaboration with Jean-Michel Fourneau [PRiSM, Université de Versailles Saint-Quentin] we consider two different applications of stochastic monotonicity in performance evaluation of networks [14]. In the first one, we assume that a Markov chain of the model depends on a parameter that can be estimated only up to a certain level and we have only an interval that contains the exact value of the parameter. Instead of taking an approximated value for the unknown parameter, we show how we can use the monotonicity properties of the Markov chain to take into account the error bound from the measurements. In the second application, we consider a well known approximation method: the decomposition into submodels. In such an approach, models of complex networks are decomposed into submodels whose results are then used as parameters for the next submodel in an iterative computation. One obtains a fixed point system which is solved numerically. In general, we have neither an existence proof of the solution of the fixed point system nor a convergence proof of the iterative algorithm. Here we show how stochastic monotonicity can be used to answer these questions. Furthermore, monotonicity properties can also help to derive more efficient algorithms to solve fixed point systems.

6.2.3.2. Markov Reward Processes and Aggregation

In a joint work with I.M. H. Vliegen [University of Twente, The Netherlands] and A. Scheller-Wolf [Carnegie Mellon University, USA] [16], we presented a new bounding method for Markov chains inspired by Markov reward theory: Our method constructs bounds by redirecting selected sets of transitions, facilitating an intuitive interpretation of the modifications of the original system. We show that our method is compatible with strong aggregation of Markov chains; thus we can obtain bounds for an initial chain by analyzing a much smaller chain. We illustrated our method by using it to prove monotonicity results and bounds for assemble-to-order systems.

6.2.3.3. Bounded State Space Truncation

Markov chain modeling often suffers from the curse of dimensionality problems and many approximation schemes have been proposed in the literature that include state-space truncation. Estimating the accuracy of such methods is difficult and the resulting approximations can be far from the exact solution. Censored Markov chains (CMC) allow to represent the conditional behavior of a system within a subset of observed states and provide a theoretical framework to study state-space truncation. However, the transition matrix of a CMC is in general hard to compute. Dayar et al. (2006) proposed DPY algorithm, that computes a stochastic bound for a CMC, using only partial knowledge of the original chain. In [32], we prove that DPY is optimal for the information they take into account. We also show how some additional knowledge on the chain can improve stochastic bounds for CMC.

6.2.4. Dynamic Systems with Local Interactions

Dynamic systems with local interactions can be used to model problems in distributed computing: gathering a global information by exchanging only local information. The challenge is two-fold: first, it is impossible to centralize the information (cells are indistinguishable); second, the cells contain only a limited information (represented by a finite alphabet $\mathcal{A}$; $\mathcal{A} = \{0, 1\}$ in our case). Two natural instantiations of dynamical systems are considered, one with synchronous updates of the cells, and one with asynchronous updates. In the first case, time is discrete, all cells are updated at each time step, and the model is known as a *Probabilistic Cellular Automaton (PCA)* (e.g. Dobrushin, R., Kryukov, V., Toom, A.: *Stochastic cellular systems: ergodicity, memory, morphogenesis*, 1990). In the second case, time is continuous, cells are updated at random instants, at most one cell is updated at any given time, and the model is known as a (finite range) *Interacting Particle System (IPS)* (e.g. Liggett, T.M.: *Interacting particle systems*, 2005).

6.2.4.1. Density Classification on Infinite Lattices and Trees

In a joint work with N. Fatès [Inria Nancy – Grand-Est], J. Mairesse and I. Marcovici [LIAFA, CNRS and Université Paris 7] [43] we consider an infinite graph with nodes initially labeled by independent Bernoulli random variables of parameter p. We address the density classification problem, that is, we want to design a (probabilistic or deterministic) cellular automaton or a finite-range interacting particle system that evolves on this graph and decides whether p is smaller or larger than $1/2$. Precisely, the trajectories should converge (weakly) to the uniform configuration with only $0's$ if $p < 1/2$, and only $1's$ if $p > 1/2$. We present solutions to that problem on $\mathbb{Z}^d$, for any $d \geq 2$, and on the regular infinite trees. For $\mathbb{Z}$, we propose some candidates that we back up with numerical simulations.

6.3. Economics of Networks

Participants: François Baccelli, Emilie Coupechoux, Marc Lelarge.

6.3.1. Diffusion and Cascading Behavior in Random Networks

The spread of new ideas, behaviors or technologies has been extensively studied using epidemic models. In [25], we consider a model of diffusion where the individuals' behavior is the result of a strategic choice. We study a simple coordination game with binary choice and give a condition for a new action to become widespread in a random network. We also analyze the possible equilibria of this game and identify conditions for the coexistence of both strategies in large connected sets. Finally we look at how can firms use social networks to promote their goals with limited information.

Our results differ strongly from the one derived with epidemic models. In particular, we show that connectivity plays an ambiguous role: while it allows the diffusion to spread, when the network is highly connected, the diffusion is also limited by high-degree nodes which are very stable. In the case of a sparse random network of interacting agents, we compute the contagion threshold for a general diffusion model and show the existence of (continuous and discontinuous) phase transitions. We also compute the minimal size of a seed of new adopters in order to trigger a global cascade if these new adopters can only be sampled without any information on the graph. We show that this minimal size has a non-trivial behavior as a function of the connectivity. Our analysis extends methods developed in the random graphs literature based on the properties of empirical distributions of independent random variables, and leads to simple proofs.

6.3.2. Coordination in Network Security Games: a Monotone Comparative Statics Approach

Malicious softwares or malwares for short have become a major security threat. While originating in criminal behavior, their impact are also influenced by the decisions of legitimate end users. Getting agents in the Internet, and in networks in general, to invest in and deploy security features and protocols is a challenge, in particular because of economic reasons arising from the presence of network externalities. In [24], [42], we focus on the question of incentive alignment for agents of a large network towards a better security. We start with an economic model for a single agent, that determines the optimal amount to invest in protection. The model takes into account the vulnerability of the agent to a security breach and the potential loss if a security breach occurs. We derive conditions on the quality of the protection to ensure that the optimal amount spent on security is an increasing function of the agent's vulnerability and potential loss. We also show that for a large class of risks, only a small fraction of the expected loss should be invested. Building on these results, we study a network of interconnected agents subject to epidemic risks. We derive conditions to ensure that the incentives of all agents are aligned towards a better security. When agents are strategic, we show that security investments are always socially inefficient due to the network externalities. Moreover alignment of incentives typically implies a coordination problem, leading to an equilibrium with a very high price of anarchy.

6.4. Point Processes, Stochastic Geometry and Random Geometric Graphs

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Pierre Brémaud, Kumar Gaurav, Mir Omid Haji Mirsadeghi.

stochastic geometry, point process, shot-noise, Boolean model, random tessellation, percolation, stochastic comparison

6.4.1. Modeling, comparison and impact of spatial irregularity of point processes on coverage, percolation, and other characteristics of random geometric models

We develop a general approach for comparison of clustering properties of point processes. It is funded on some basic observations allowing to consider void probabilities and moment measures as two complementary tools for capturing clustering phenomena in point processes. As expected, smaller values of these characteristics indicate less clustering. Also, various global and local functionals of random geometric models driven by point processes admit more or less explicit bounds involving the void probabilities and moment measures, thus allowing to study the impact of clustering of the underlying point process. When stronger tools are needed, dcx ordering of point processes happens to be an appropriate choice, as well as the notion of (positive or negative) association, when comparison to the Poisson point process is concerned. The whole approach has been worked out in a series of papers [62], [63], [64], [65]. This year we have prepared revisions of the two latter ones, from which [65] is now accepted for the publication in Adv. Appl. Probab. We have also prepared a review article [53] for *Lecture Notes in Mathematics*, Springer.

6.4.1.1. AB random geometric graphs

We investigated percolation in the AB Poisson-Boolean model in d-dimensional Euclidean space, and asymptotic properties of AB random geometric graphs on Poisson points in $[0,1]^d$. The AB random geometric graph we studied is a generalization to the continuum of a bi-partite graph called the AB percolation model on discrete lattices. Such an extension is motivated by applications to secure communication networks and frequency division duplex networks. The AB Poisson Boolean model is defined as a bi-partite graph on two independent Poisson point processes of intensities λ and μ in the d-dimensional Euclidean space in the same manner as the usual Boolean model with a radius r. We showed existence of AB percolation for all $d \geq 2$, and derived bounds for a critical intensity. Further, in $d = 2$, we characterize a critical intensity. The set-up for AB random geometric graphs is to construct a bi-partite graph on two independent Poisson point process of intensities n and cnin the unit cube. We provided almost sure asymptotic bounds for the connectivity threshold for all $c > 0$ and a suitable choice of radius cut-off functions $r_n(c)$. Further for $c < c_0$, we derived a weak law result for the largest nearest neighbor radius. This work appeared in [27].

6.4.2. Random Packing Models

Random packing models (RPM) are point processes (p.p.s) where points which "contend" with each other cannot be simultaneously present. These p.p.s play an important role in many studies in physics, chemistry, material science, forestry and geology. For example, in microscopic physics, chemistry and material science, RPMs can be used to describe systems with hard-core interactions. Applications of this type range from reactions on polymer chains, chemisorption on a single-crystal surface, to absorption in colloidial systems. In these models, each point (molecule, particle,$\cdots$) in the system occupies some space, and two points with overlapping occupied space contend with each other. Another example is the study of seismic and forestry data patterns, where RPMs are used as a reference model for the data set under consideration. In wireless communications, RPMs can be used to model the users simultaneously accessing the medium in a wireless network using Carrier Sensing Medium Access (CSMA). In this context, each point (node, user, transmitter,$\cdots$) does not occupy space but instead generates interference to other points in the network. Two points contend with each other if either of them generates too much interference to the other. Motivated by this kind of application, we studied in [66] the generating functionals of several models of random packing processes: the classical Matérn hard-core model; its extensions, the k-Matérn models and the ∞-Matérn model, which is an example of random sequential packing process. The main new results are: 1) A sufficient condition for the ∞-Matérn model to be well-defined (unlike the other two, the ∞-Matérn model may not be well-defined on unbounded space); 2) the generating functional of the resulting point process which is given for each of the three models as the solution of a differential equation; 3) series representation and bounds on the generating functional of the packing models; 4) moment measures and other useful properties of the considered packing models which are derived from their generating functionals.

6.4.3. Extremal and Additive Matérn Point Processes

In the simplest Matérn point processes, one retains certain points of a Poisson point process in such a way that no pairs of points are at distance less than a threshold. This condition can be reinterpreted as a threshold condition on an extremal shot–noise field associated with the Poisson point process. In a joint work with P. Bermolen [Universidad de la República, Montevideo, Uruguay] [60], we studied extensions of Matérn point processes where one retains points that satisfy a threshold condition based on an *additive* shot–noise field of the Poisson point process. We provide an analytical characterization of the intensity of this class of point processes and we compare the packing obtained by the extremal and additive schemes and certain combinations thereof.

6.4.4. Spatial Birth and Death Point Processes

In collaboration with F. Mathieu [Inria GANG] and Ilkka Norros [VTT, Finland], we continued studying a new spatial birth and death point process model where the death rate is a shot noise of the point configuration. We showed that the spatial point process describing the steady state exhibits repulsion. We studied two asymptotic regimes: the fluid regime and the hard–core regime. We derived closed form expressions for the mean (and in some cases the law) of the latency of points as well as for the spatial density of points in the steady state of each regime. A paper on the matter will be presented at Infocom 13.

6.4.5. A population model based on a Poisson line tessellation

In [44], we introduce a new population model. Taking the geometry of cities into account by adding roads, we build a Cox process driven by a Poisson line tessellation. We perform several shot-noise computations according to various generalizations of our original process. This allows us to derive analytical formulas for the uplink coverage probability in each case.

6.4.6. Information Theory and Stochastic Geometry

In a joint work with V. Anantharam [UC Berkeley], we study the Shannon regime for the random displacement of stationary point processes. We currently investigate Multiple Access Channels.

6.4.7. Navigation on Point Processes and Graphs

The thesis of Mir Omid Mirsadeghi [6] studied optimal navigations in wireless networks in terms of first passage percolation on some space-time SINR graph. It established both “positive” and “negative” results on the associated percolation delay rate (delay per unit of Euclidean distance, also called time constant in the classical terminology of percolation). The latter determines the asymptotics of the minimum delay required by a packet to progress from a source node to a destination node when the Euclidean distance between the two tends to infinity. The main negative result states that the percolation delay rate is infinite on the random graph associated with a Poisson point process under natural assumptions on the wireless channels. The main positive result states that when adding a periodic node infrastructure of arbitrarily small intensity to the Poisson point process, the percolation delay rate is positive and finite.

A new direction of research was initiated aiming at defining a new class of measures on a point process which are invariant under the action of a navigation on this point process. This class of measures has properties similar to Palm measures of stationary point processes; but they cannot be defined in the classical framework of Palm measures.

6.5. Random Graphs and Combinatorial Optimization

Participants: Emilie Coupechoux, Kumar Gaurav, Mathieu Leconte, Marc Lelarge.

random graphs, combinatorial optimization, local weak convergence, diffusion, network games.

6.5.1. Matchings in infinite graphs

In [13] with Charles Bordenave [CNRS-Université de Toulouse] and Justin Salez [Université Paris 7], we proved that for any sequence of (deterministic or random) graphs converging locally, the corresponding sequence of normalized matching numbers converges, and this limit depends only on the limit of the graph sequence. In the particular case where this limit is a unimodular Galton Watson tree, we were able to compute explicitly the value for the limit of the sequence of (normalized) matching numbers. This leads to an explicit formula that considerably extends the well-known one by Karp and Sipser for Erdős-Rényi random graphs.

We considered a natural family of Gibbs distributions over matchings on a finite graph, parameterized by a single positive number called the temperature. The correlation decay technique can be applied for the analysis of matchings at positive temperature and allowed us to establish the weak convergence of the Gibbs marginal as the underlying graph converges locally. However for the zero temperature problem (i.e. maximum matchings), we showed that there is no correlation decay even in very simple cases. By using a complex temperature and a half-plane property due to Heilmann and Lieb, we were able to let the temperature tend to zero and obtained a limit theorem for the asymptotic size of a maximum matching in the graph sequence.

6.5.2. Convergence of Multivariate Belief Propagation, with Applications to Cuckoo Hashing and Load Balancing

In [58], with Laurent Massoulié [Inria-MSR], we extend the results obtained previously on the asymptotic size of maximum matchings in random graphs converging locally to Galton-Watson trees to so-called capacitated b-matchings (with non-unitary capacity at vertices as well as constraints on individual edges). Compared to the matching case, this involves studying the convergence of a message passing algorithms which transmits vectors instead of single real numbers. We also look further into an application of these results to large multiple-choice hashtables. In particular, cuckoo hashing is a popular and simple way to build a hashtable where each item is only allowed to be assigned keys within a predetermined, random subset of all keys. In this context, it is important to determine the load threshold under which cuckoo hashing will succeed with high probability in building such a hashtable. The results on the density of maximum capacitated b-matchings allow to determine this threshold.

6.5.3. A new approach to the orientation of random hypergraphs

A h-uniform hypergraph $H = (V, E)$ is called (l, k)-orientable if there exists an assignment of each hyperedge e to exactly l of its vertices such that no vertex is assigned more than k hyperedges. Let $H_{n,m,h}$ be a hypergraph, drawn uniformly at random from the set of all h-uniform hypergraphs with n vertices and m edges. In [41], we determine the threshold of the existence of a (l, k)-orientation of $H_{n,m,h}$ for $k \geq 1$ and $h > l \geq 1$, extending recent results motivated by applications such as cuckoo hashing or load balancing with guaranteed maximum load. Our proof combines the local weak convergence of sparse graphs and a careful analysis of a Gibbs measure on spanning subgraphs with degree constraints. It allows us to deal with a much broader class than the uniform hypergraphs.

6.5.4. Bipartite graph structures for efficient balancing of heterogeneous loads

In [40], with Laurent Massoulié [Inria-MSR], we look into another application of the results on the asymptotic maximum size of b-matchings to large scale distributed content service platforms, such as peer-to-peer video-on-demand systems. In this context, the density of maximum b-matchings corresponds to the maximum fraction of simultaneously satisfiable requests, when the service resources are limited and each server can only handle requests for a predetermined subset of the contents which it has stored in memory. An important design aspect of such systems is the content placement strategy onto the servers depending on the estimated content popularities; the results obtained allow to characterize the efficiency of such placement strategies and the optimal strategies in the limit of large storage capacity at servers are determined.

6.5.5. Flooding in Weighted Random Graphs

In a joint work [8] with Hamed Amini [EPFL] and Moez Draief [Imperial College London], we studied the impact of the edge weights on distances in diluted random graphs. We interpret these weights as delays, and take them as i.i.d exponential random variables. We analyzed the edge flooding time defined as the minimum time needed to reach all nodes from one uniformly chosen node, and the edge diameter corresponding to the worst case edge flooding time. Under some regularity conditions on the degree sequence of the random graph, we showed that these quantities grow as the logarithm of n, when the size of the graph n tends to infinity. We also derived the exact value for the prefactors.

These allowed us to analyze an asynchronous randomized broadcast algorithm for random regular graphs. Our results show that the asynchronous version of the algorithm performs better than its synchronized version: in the large size limit of the graph, it will reach the whole network faster even if the local dynamics are similar on average.

6.5.6. Upper deviations for split times of branching processes

In [9], upper deviation results are obtained for the split time of a supercritical continuous-time Markov branching process. More precisely, with Hamed Amini [EPFL], we establish the existence of logarithmic limits for the likelihood that the split times of the process are greater than an identified value and determine an expression for the limiting quantity. We also give an estimation for the lower deviation probability of the split times which shows that the scaling is completely different from the upper deviations.

6.5.7. Epidemics in random clustered networks

In [54], we study a model of random networks that has both a given degree distribution and a tunable clustering coefficient. We consider two types of growth processes on these graphs: diffusion and symmetric threshold model. The diffusion process is inspired from epidemic models. It is characterized by an infection probability, each neighbor transmitting the epidemic independently. In the symmetric threshold process, the interactions are still local but the propagation rule is governed by a threshold (that might vary among the different nodes). An interesting example of symmetric threshold process is the contagion process, which is inspired by a simple coordination game played on the network. Both types of processes have been used to model spread of new ideas, technologies, viruses or worms and results have been obtained for random graphs with no clustering. In this paper, we are able to analyze the impact of clustering on the growth processes. While clustering inhibits the diffusion process, its impact for the contagion process is more subtle and depends on the connectivity of the graph: in a low connectivity regime, clustering also inhibits the contagion, while in a high connectivity regime, clustering favors the appearance of global cascades but reduces their size. For both diffusion and symmetric threshold models, we characterize conditions under which global cascades are possible and compute their size explicitly, as a function of the degree distribution and the clustering coefficient. Our results are applied to regular or power-law graphs with exponential cutoff and shed new light on the impact of clustering.

6.5.8. Leveraging Side Observations in Stochastic Bandits

The paper [37] considers stochastic bandits with side observations, a model that accounts for both the exploration/exploitation dilemma and relationships between arms. In this setting, after pulling an arm i, the decision maker also observes the rewards for some other actions related to i. We will see that this model is suited to content recommendation in social networks, where users' reactions may be endorsed or not by their friends. We provide efficient algorithms based on upper confidence bounds (UCBs) to leverage this additional information and derive new bounds improving on standard regret guarantees. We also evaluate these policies in the context of movie recommendation in social networks: experiments on real datasets show substantial learning rate speedups ranging from 2.2x to 14x on dense networks.

6.5.9. Universality in Polytope Phase Transitions and Message Passing Algorithms

In [28], with Mohsen Bayati and Andrea Montanari [Stanford], we consider a class of nonlinear mappings F in R^N indexed by symmetric random matrices A in $R^{N\times N}$ with independent entries. Within spin glass theory, special cases of these mappings correspond to iterating the TAP equations and were studied by Erwin Bolthausen. Within information theory, they are known as 'approximate message passing' algorithms. We study the high-dimensional (large N) behavior of the iterates of F for polynomial functions F, and prove that it is universal, i.e. it depends only on the first two moments of the entries of A, under a subgaussian tail condition. As an application, we prove the universality of a certain phase transition arising in polytope geometry and compressed sensing. This solves -for a broad class of random projections- a conjecture by David Donoho and Jared Tanner.

6.5.10. Far-out Vertices In Weighted Repeated Configuration Model

In [34] we consider an edge-weighted uniform random graph with a given degree sequence (Repeated Configuration Model) which is a useful approximation for many real-world networks. It has been observed that the vertices which are separated from the rest of the graph by a distance exceeding certain threshold play an important role in determining some global properties of the graph like diameter, flooding time etc., in spite of being statistically rare. We give a convergence result for the distribution of the number of such far-out vertices. We also make a conjecture about how this relates to the longest edge of the minimal spanning tree on the graph under consideration.

7. Bilateral Contracts and Grants with Industry

7.1. Laboratoire Commun Alcatel-lucent Bell Labs / Inria

Participant: Anne Bouillard.

The joint laboratory was lauched on 2008. The objective of this collaboration is to contribute to the autonomic networking trend. On Inria's side, the research for this ADR (*action de recherche*) is mainly located at DISTRIBCOM team-project. On TREC's side, it involves the co-supervision of the thesis of Aurore Junier and has led to one publication [30] and a patent application [57].

7.2. CIFRE Grant of Technicolor

Participants: Mathieu Leconte, Marc Lelarge, Laurent Massoulié.

The CIFRE grant of Mathieu started in January 2011. The topic bears on information dissemination and recommendation in social networks. The distribution of multimedia content and the use of social networks like Facebook, Orkut, etc. are booming in today's networks. These social networks are also increasingly used for dissemination and recommendation of content. The objective of the thesis will be to develop an understanding of how information disseminates in social networks based on the type of information, user tastes, and the topological structure of these networks. This study will result in developing methods for more effective dissemination of content.

7.3. CIFRE Grant of Orange

Participants: Bartłomiej Błaszczyszyn, Miodrag Jovanović.

The CIFRE grant of Miodrag started in 2012. The topic bears on the evaluation and optimization of the QoS for new services in cellular networks. This year a work on feasible bit-rates in the MIMO LTE (Long Term Evolution) cellular networks has been presented in [39]. We have been also studying real-time streaming (like mobile TV) in wireless cellular networks. This work is reported in [50] submitted for the publication.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. LINCS

TREC participates in the Laboratory of Information, Networking and Communication Sciences (LINCS); http://www.lincs.fr/ created on October 28th, 2010, by three French institutions of higher education and research: Inria, Institut Télécom and UPMC. Alcatel-Lucent joined the LINCS in February 2011 as a strategic partner.

8.1.2. Digiteo ACRON

Participant: Bartłomiej Błaszczyszyn.

Project *Analyse et Conception de Réseaux Sans Fil Auto-Organisés* (ACRON) started in 2011. Coordinator: Supélec (Télécommunications), Partners: Inria HIPERCOM, Université Paris-Sud, IEF. Trec is associated partner.

The objective of this project is to work on characterization of the fundamental performance limits of large self-organizing wireless networks and develop distributed and self-organizing communication techniques that will approach the theoretical limits.

8.2. National Initiatives

8.2.1. ANR CMON

Participants: François Baccelli, Florence Bénézit, Darryl Veitch.

The ANR project CMON, jointly with Technicolor, LIP6, the Inria project-team Planète and the community http://wiki.grenouille.com/index.php/CMON was continued for 6 months. This project is focused on the development of end-to-end measurement for Internet that can be deployed by end-users, without any support from ISP. Our work over this period focused on wireless network tomography.

8.2.2. ANR PEGASE

Participants: Abir Benabid, Anne Bouillard.

TREC is a partner of the 3-year ANR project called PEGASE, jointly with ENS Lyon, the Inria project-team MESCAL, ONERA, Real-Time-at-Work (start-up) and Thalès. This project is focused on the analysis of critical embedded networks using algebraic tools. The aim is to apply these techniques to AFDX and Spacewire architectures. Abir Benabid was hired until January 2012.

8.2.3. ANR GAP

Participants: Marc Lelarge, Emilie Coupechoux, Mathieu Leconte.

Over the last few years, several research areas have witnessed important progress through the fruitful collaboration of mathematicians, theoretical physicists and computer scientists. One of them is the cavity method. Originating from the theory of mean field spin glasses, it is key to understanding the structure of Gibbs measures on diluted random graphs, which play a key role in many applications, ranging from statistical inference to optimization, coding and social sciences.

The objective of this project (2012-2016) is to develop mathematical tools in order to contribute to a rigorous formalization of the cavity method. We intend to launch two new research lines:

- From local to global, the cavity method on diluted graphs. We will study the extent to which the global properties of a random process defined on some graph are determined by the local properties of interactions on this graph. To this end, we will relate the cavity method to the analysis of the complex zeros of the partition function, an approach that also comes from statistical mechanics. This will allow us to apply new techniques to the study of random processes on large diluted graphs and associated random matrices.
- Combinatorial optimization, network algorithms, statistical inference and social sciences. Motivated by combinatorial optimization problems, we will attack long-standing open questions in theoretical computer science with the new tools developed in the first project. We expect to design new distributed algorithms for communication networks and new algorithms for inference in graphical models. We will also analyze networks from an economic perspective by studying games on complex networks.

8.2.4. ANR MAGNUM

Participant: Ana Bušić.

Ana Bušić is participating (pôle de rattachement: LIP6, UPMC) in the 4-year ANR project MAGNUM (Méthodes Algorithmiques pour la Génération aléatoire Non Uniforme: Modèles et applications), 2010–2014; http://www.lix.polytechnique.fr/~rossin/ANR/Magnum/www/. The central theme of the MAGNUM project is the elaboration of complex discrete models that are of broad applicability in several areas of computer science. A major motivation for the development of such models is the design and analysis of efficient algorithms dedicated to simulation of large discrete systems and random generation of large combinatorial structures.

8.2.5. GdR Stochastic Geometry

Participants: François Baccelli, Bartłomiej Błaszczyszyn.

TREC is a member of the Research Group GeoSto (Groupement de recherche, GdR 3477) http://gdr-geostoch.math.cnrs.fr/ on Stochastic Geometry led by Pierre Calka (Université de Rouen). This is a collaboration framework for all French research teams working in the domain of *spatial stochastic modeling*, both on theory development and in applications. The kickoff meeting was organized this year in March at the University of Rouen; http://gdr-geostoch.math.cnrs.fr/workshop_Rouen. It brought together more than 80 researchers from France and Europe.

8.2.6. ARC OCOQS

Participant: Ana Bušić.

Two-year Inria Collaborative action *Action de recherche collaborative (ARC)* OCOQS "Optimal threshold policies in COntrolled Queuing Systems" OCOQS started in 2011. Coordinator: Ana Bušić, Participants: Alain Jean-Marie (MAESTRO, Inria Sophia-Antipolis), Emmanuel Hyon (University of Paris Ouest and LIP6), Ingrid Vliegen (University of Twente); http://www.di.ens.fr/~busic/OCOQS. The research subject is the optimal control of stochastic processes, with applications to the control of networks and manufacturing systems. The principal aim is to widen the set of mathematical techniques that can be used to prove that optimal policies are of threshold type, thereby widening the set of classes of models that can be effectively solved exactly or numerically handled in practice. A one-day workshop on Structural Properties in Markov Decision Processes was organized this year in January at Inria, Paris; http://www.di.ens.fr/~busic/OCOQS/workshop.html.

8.3. European Initiatives

8.3.1. Collaborations in European Programs FP7

Participant: All Trec.

- European Network of Excellence (NoE), http://euronf.enst.fr/en_accueil.html;
- Project acronym: Euro-NF;
- Duration: January 2008 - June 2012;
- Coordinator: D. Kofman (Intitut Télécom);
- Partners: about 30 partners;
- Abstract: This NoE is focused on the next generation Internet. Its main target is to integrate the research effort of the partners to be a source of innovation and a think tank on possible scientific, technological and socio-economic trajectories towards the network of the future. Euro-NF is supported by the theme "Information and Communication Technologies (ICT)" under the 7th Framework Programme of the European Community for RTD. Euro-NF is a continuation of Euro-NGI

8.3.2. Collaborations in European Programs, except FP7

8.3.2.1. EIT ICT Labs

Participants: François Baccelli, Fabien Mathieu, Mir Omid Mirsadeghi, Rémi Varloot.

This grant in collaboration with Fabien Mathieu (GANG) was focused on the analysis of P2P systems, primarily in the context of wireless. Our partner Ilkka Norros (VTT) visited several times to work on the matter. We hired an Intern from ENS (Rémi Varloot). Our efforts led to a joint paper accepted at Infocom'13. In spite of the success of this collaboration, the grant will not be continued (due to the lack of proper 'Catalyst' with EIT ICT Labs).

8.4. International Initiatives

8.4.1. Inria Associate Teams

8.4.1.1. IT-SG-WN

- Title: Information Theory, Stochastic Geometry, Wireless Networks
- Inria principal investigator: François Baccelli
- International Partner:

  Institution: University of California Berkeley (United States)

  Laboratory: EECS Department

  Researcher: Venkat Anantharam, Anant Sahai, David Tse.
- International Partner:

Institution: Stanford University (United States)

Laboratory: EE

Researcher: Abbas El Gamal.

- Duration: 2011 - 2013
- See also: http://www.di.ens.fr/~baccelli/IT_SG_WN_web_site.htm
- The activity of this proposal is centered on the inter-play between stochastic geometry and network information theory, whith a particular emphasis on wireless networks. In terms of research, three main lines of thought will be pursued:1. Error exponents and stochastic geometry2. Stochastic geometry and network Information Theory3. Cognitive radio and stochastic geometry

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Venkat Anantharam (University of Berkeley),
- Daryl Daley (University of Melbourne),
- Christian Hirsch (University of Ulm),
- Guenter Last (KIT Germany),
- Ravi Mazumdar (University of Waterloo, Inria visiting professor),
- Naoto Miyoshi (Tokyo Institute of Technology),
- Ilkka Norros (VTT, Finland).

8.5.2. Internships

- Julieta BOLLATI (from Apr 2012 until Jun 2012)

  Subject: Optimal threshold computation in controlled queueing systems

  Institution: National University of Rosario (Argentina)

8.5.3. Visits to International Teams

- François Baccelli is one of the two recipients of the Simons Math+X Chair (https://simonsfoundation.org/funding/funding-opportunities/mathematics-physical-sciences/mathx/mathx-encouraging-interactions-2011-chair-recipients/ and is now on the faculty at UT Austin. He keeps a part time position in TREC.

9. Dissemination

9.1. Scientific Animation

9.1.1. TREC's seminar

The following scientists gave talks on Trec's seminar in 2012 (see http://www.di.ens.fr/~trec/seminar.html for details)

- **Emilie Coupechoux** (TREC/Lip6), PhD thesis defense /Dec 10, 2012/ Talking on: "Analyse de grands graphes aléatoires";
- **Mir Omid Haji Mirsadeghi** (TREC), PhD thesis defense /Jul 11, 2012/ Talking on: "Routage sur les graphes géométriques aléatoires";
- **Frederic Morlot** (TREC), PhD thesis defense /Jul 2, 2012/ Talking on: "Processus spatio-temporels en géométrie stochastique et application à la modélisation des réseaux de télécommunication";
- **Mathieu Feuillet** /Jun 7, 2012/ Talking on: "Scaling Analysis of a Transient Stochastic Network";

- **D. J. Daley** (The University of Melbourne) /May 24, 2012/ Talking on: "Dimension Walks and Schoenberg Spectral Measures for Isotropic Random Fields";
- **Florian Simatos** (Eindhoven University of Technology) /May 16, 2012/ Talking on: "Scaling limits of regenerative processes via the convergence of their excursions: some applications to queueing theory";
- **Chandramani Singh** (TREC) /Apr 18, 2012/ Talking on: "Optimal Message Forwarding in Delay Tolerant Networks with Multiple Destinations";
- **Holger-Paul Keeler** (Inria TREC) /Apr 5, 2012/ Talking on: "A Greedy Routing Model";
- **Alain Jean-Marie** (Inria MAESTRO) /Apr 3, 2012/ Talking on: "Variations on the Data Placement problem";
- **Hermann Thorisson** (University of Iceland) /Mar 16, 2012/ Talking on: "Unbiased shifts of Brownian motion";
- **Lenka Zdeborova** (Institut de Physique Theorique, CEA) /Mar 8, 2012/ Talking on: "Statistical-physics-based reconstruction in compressed sensing";
- **Gideon Weiss** (Haifa University) /Mar 1, 2012/ Talking on: "Skill based service systems";
- **Francis Comets** (Université Paris Diderot) /Feb 23, 2012/ Talking on: "Transmission d'information sous contraintes du capital d'émission";
- **Guenter Last** (Karlsruhe Institute of Technology) /Feb 21, 2012/ Talking on: "Fock space representation and variational analysis of Poisson functionals";
- **Sergei Zuyev** (Chalmers University of Technology) /Feb 21, 2012/ Talking on: "undefined";
- **Harpreet S. Dhillon** (UT Austin) /Feb 15, 2012/ Talking on: "Analysis of K-tier Heterogeneous Cellular Networks";
- **Bernadette Charron-Bost** (LIX) /Feb 2, 2012/ Talking on: "On the Transience of Linear Max-Plus Dynamical Systems";
- **Christian Hirsch** (University of Ulm, Germany) /Jan 23, 2012/ Talking on: "Connectivity and first-passage percolation of random geometric graphs related to minimal spanning forests";

9.1.2. Reading groups

- The reading group on Random Graphs was animated by A. Bouillard and A. Giovanidis; see http://www.di.ens.fr/~bouillar/GdL/index.html
- The reading group on Graphs, Algorithms and Probability is animated by Marc Lelarge; see http://www.di.ens.fr/~lelarge/GdT-GAP.html

9.2. Teaching – Supervision – Juries

9.2.1. Teaching

ENS Paris

- Undergraduate course (master level, DIENS) by M. Lelarge and M. Leconte, on Information Theory and Coding (24h + 24h of exercise session).
- Course on Communication Networks (master level, DIENS) by F. Baccelli, A. Bouillard and A. Bušić (24h + 24h of exercice sessions).
- Course on Network Modeling (master level, MPRI) by F. Baccelli and A. Bouillard (24h)
- Undergraduate course (master level, DIENS) by A. Bouillard and P. Brémaud, on Random Structures and Algorithms (35h + 28h of exercise session).
- Undergraduate exercise session (master level, DIENS) by A. Bouillard on formal languages, computability and complexity (12h).

ENS Cachan - Antenne de Bretagne

– Preparation to the oral exams of the agregation of mathematics (computer science option) by A. Bouillard (11h).

UPMC, Paris 6

– Graduate Course on point processes, stochastic geometry and random graphs (program ”Master de Sciences et Technologies”), B. Błaszczyszyn and L. Massoulié (45h).

– Undergraduate course onconception of algorithms and applications (Licence Informatique, 3rd year), A. Bušić (24h)

Université de Versailles Saint-Quentin-en-Yvelines

– Graduate course on simulation (M2 COSY), A. Bušić (6h).

Université Paris Ouest Nanterre La Défense

– Network half of an undergraduate course (L3 Licence MIAGE) by M. Leconte on Systems and Networks (18h)

9.2.2. Supervision

- PhD: **Emilie Coupechoux**, “Analysis of large random graphs”, started in September 2009, defended on December 10, 2012, adviser M. Lelarge, F. Baccelli; see [5].
- PhD: **Mir Omid Haji Mirsadeghi**, “Routing on Point Processes”, started in 2009, defended on Julay 11, 2012, adviser F. Baccelli; see [6].
- PhD: **Frédéric Morlot**, “Mobility Models for Communication Networks”, started in 2008, defended on Julay 2, 2012; adviser F. Baccelli; see [7].
- PhD in progress: **Tien Viet Nguyen**, “Random Packing Models”, started in 2009, adviser F. Baccelli.
- PhD in progress: **Mathieu Leconte**, “Propagation d’information et recommandations dans les réseaux sociaux”, started in January 2011, adviser M. Lelarge, F. Baccelli;
- PhD in progress: **Aurore Junier**, “Tuning parameters in routing protocoles” started in September 2010, advisers A. Bouillard and C. Jard;
- PhD in progress: **Kumar Gaurav**, “ Convex comparison of network architectures” started in October 2011, adviser B. Błaszczyszyn;
- PhD in progress: **Miodrag Jovanović**, “Evaluation and optimization of the quality perceived by mobile users for new services in cellular networks” started in January 2012, adviser B. Błaszczyszyn;
- PostDoc’s: Anastasios Giovanidis, Holger Paul Keeler, Chandramani Singh.

9.2.3. Juries

François Baccelli *PhD defence* of **Eduardo Ferraz** (Telecom ParisTech, February 2012).

Bartłomiej Błaszczyszyn *PhD defence* of **Kehao Wang** (Paris Sud, June 2012, reviewer), **Arash Behboodi** (Supelec, June 2012), **Thanh Tung Vu** (Telecom PrisTech, September 2012), **Salman Malik** (Inria/UPMC, November 2012), *associate-professor hiring-committee* at Département Informatique, Faculté des Sciences et Technologies, Université de Lorraine (Section 27, Poste 27 PR 072, May 2012).

Anne Bouillard *PhD defence* of **Laurent Jouhet** (ENS Lyon, november, 7th), *admission jury* at the ENS Cachan entrance exam.

9.3. Invitations and Participation in Conferences

François Baccelli

– Keynotes:

   * Lecture at "Semaine des mathématiques dans l’académie Nancy-Metz, Institut Elie Cartan de Nancy" March 2012 http://www.ac-nancy-metz.fr/semaine-des-mathematiques-du-12-au-18-mars-2012-31219.kjsp?RH=WWW

    - Lecture on stochastic geometry for the inauguration of the Simons Math+X Chair https://simonsfoundation.org/funding/funding-opportunities/mathematics-physical-sciences/mathx/mathx-encouraging-interactions-2011-chair-recipients/
    - Keynote Lecture at Stochmod'12, Paris, June 2012, on stochastic geometry http://www.lgi.ecp.fr/StochMod2012/pmwiki.php/Main/HomePage
    - Lecture at Collège de France, Paris, Dec. 2012, on the mathematics of peer-to-peer networks http://www.college-de-france.fr/site/en-bernard-chazelle/seminar-2012-12-20-15h00.htm
  - Presentations in the following conferences or seminars:
    - Stochastic Networks, MIT, June-2012, http://stoch-nets-2012.lids.mit.edu/
    - Séminaire Inria at Silicon Valley, Paris, May 2012, https://project.inria.fr/inria-siliconvalley/
    - GdR Isis Day, Telecom ParisTech, April 2012 http://gdr-isis.fr/index.php?page=reunion&idreunion=163.
    - Workshop "Information Theory for Cooperative Networks", Institut Henri Poincaré, March 2012.
    - GdR Géométrie Stochastique Conference, Rouen, March 2012, http://gdr-geostoch.math.cnrs.fr/workshop_Rouen/index.html
    - IIT Madras, India, January 2012.
    - IIS Bangalore, India, January 2012 http://math.iisc.ernet.in/pastevents-conf/invited_speakers.htm.

Bartłomiej Błaszczyszyn

  - Keynotes:
    - SpaSWiN 2012, Paderborn Germany, May 2012; http://www.spaswin.org/
  - Presentations in the following conferences or seminars:
    - GdR Géométrie Stochastique Conference, Rouen, March 2012; http://gdr-geostoch.math.cnrs.fr/workshop_Rouen/index.html
    - WiOpt, Paderborn Germany, May 2012; http://wi-opt.cs.upb.de/WiOpt_2012/Home.html
    - TREC inria@siliconvalley Seminar "Random Spatial Models in Communication Science" Inria, Paris, June 2012

Anne Bouillard

  - Presentations in the following conferences or seminars:
    - Valuetools 2012 (invited paper) + regular paper, Cargèse, October, 2012

Ana Bušić

  - Presentations in the following conferences or seminars:
    - Seminar at Algorithms and Theory group, Google, NY,
    - C3 Guest Lecture Series, Electrical and Computer Engineering department, University of Florida http://ccc.centers.ufl.edu/?q=Ana_Busic,
    - IEEE Conference on Decision and Control, Maui, USA http://control.disp.uniroma2.it/cdc2012/,
  - Technical Program Committee member of Sigmetrics 2012. http://www.sigmetrics.org/sigmetrics2012

Emilie Coupechoux

- Presentations in the following conferences or seminars:
  * Séminaire RAP, Rocquencourt (France), January 2012, https://team.inria.fr/rap/seminars/
  * Journées Aléa, Marseille (France), March 2012, http://lipn.univ-paris13.fr/alea2012/index.html
  * Séminaire LIP6, Paris (France), April 2012, http://www.complexnetworks.fr/events/
  * Journées Rescom, Paris (France), November 2012, http://rescom.inrialpes.fr/?p=410
  * Colloque 'Réseaux d'interactions Plantes-Pollinisateurs', Lille (France), December 2012, http://math.univ-lille1.fr/~tran/journeesplantespollinisateursreseaux.html

Anastasios Giovanidis

- Presentations in the following conferences or seminars:
  * IEEE Wireless Communications and Networking Conference (WCNC), Paris-France, April, 2012, http://www.ieee-wcnc.org/2012/
  * 16th International ITG Workshop on Smart Antennas (WSA), Dresden-Germany, March, 2012, http://wsa2012.com/
  * 21st International Symposium on Mathematical Programming (ISMP), Berlin-Germany, August, 2012, http://ismp2012.mathopt.org/

Mathieu Leconte

- Presentations in the following conferences or seminars:
  * workshop Bridging statistical physics and optimization, inference and learning, École de Physique des Houches, February-12, http://www.espci.fr/usr/fk/LESHOUCHES/home.htm
  * workshop Journées ALÉA, CIRM at Marseille-Luminy, March-12, http://lipn.univ-paris13.fr/alea2012/
  * conference Sigmetrics, Imperial College London, June-12, http://www.sigmetrics.org/sigmetrics2012/

Marc Lelarge

- Keynotes:
  * conference SIGMETRICS, London, UK http://www.sigmetrics.org/sigmetrics2012/program.php
- Presentations in the following conferences or seminars:
  * Network Science in Electrical Engineering and Computer Science, Indian Institute of Science, Bangalore. http://www.icts.res.in/program/details/283/
  * conference SODA, Kyoto, Japan http://www.siam.org/meetings/da12/
  * Stochastic Analysis Seminar, Oxford, UK http://www.oxford-man.ox.ac.uk/events/past/seminar/all
  * Models of sparse graphs and network algorithms, Banff, Canada http://www.birs.ca/events/2012/5-day-workshops/12w5004
  * conference IEEE INFOCOM, Orlando, USA http://www.ieee-infocom.org/2012/
  * NIPS 2012 Workshop: Algorithmic and Statistical Approaches for Large Social Networks, Lake Tahoe, USA http://www.datalab.uci.edu/nips-workshop-2012/

Frédéric Morlot

* Presentations in the following conferences or seminars:
  + SpaSWiN, Paderborn Germany, May 2012; http://www.spaswin.org

10. Bibliography

Major publications by the team in recent years

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[2] F. BACCELLI, B. BŁASZCZYSZYN. , *Stochastic Geometry and Wireless Networks, Volume II — Applications*, Foundations and Trends in Networking, NoW Publishers, 2009, vol. 4, No 1–2, pp. 1–312, http://hal.inria.fr/inria-00403040

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

[4] P. BRÉMAUD. , *Initiation aux Probabilites et aux chaines de Markov*, Springer-Verlag, 2009, 315 p.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[5] E. COUPECHOUX. , *Analysis of Large Random Graphs*, Université Paris Diderot, 2012

[6] M. O. MIRSADEGHI. , *Routage sur les graphes géométriques aléatoires*, Université Pierre et Marie Curie, Paris, France, 2012

[7] F. MORLOT. , *Processus spatio-tempoels en géométrie stochastique et application á la modélisation des réseaux de tél'ecommunication*, Télécom Paris, France, 2012

Articles in International Peer-Reviewed Journals

[8] H. AMINI, M. DRAIEF, M. LELARGE. *Flooding in Weighted Sparse Random Graphs*, in "SIAM Journal on Discrete Mathematics", 2013, vol. 27, n^{o} 1, pp. 1-26, http://dx.doi.org/10.1137/120865021

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