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Project-Team Trec

Network Theory and Communications

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Theme : Networks and Telecommunications

Activity Report

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TREC is a joint INRIA-ENS project-team.

1. 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, the control and the design of communication networks and protocols. Its methodological activities are combined with projects defined with industrial partners, notably Thomson, Alcatel-Lucent 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, mesh, ad-hoc, sensor, etc.): coverage and load analysis, power control, evaluation and optimization of the transport capacity, self organization;

- stochastic network dynamics, with focus on classical topics for TREC like rare events or stability, and new ones like simulation (in particular perfect simulation) and statistics (in particular inverse problems);
- economics of networks; a new domain opened in 2008: 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.
- combinatorial optimization and analysis of algorithms: random graphs, belief propagation.

3. Scientific Foundations

3.1. Scientific Foundations

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

- **Modeling and control of communication networks.** Here we mean admission control, flow regulation and feedback control *à la TCP*. 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 quality of service. We currently use our understanding of the dynamics of these protocols on Split TCP, as used in wireless access networks and in peer-to-peer overlays, and on variants of TCP meant to reach higher throughputs such as scalable TCP.
- **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, our 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. Our general goals are twofold: 1) to propose a strategy for the densification and parameterization of UMTS and future OFDM networks that is optimized for both voice and data traffic; 2) to design new self organization and self optimization protocols for cellular networks e.g. for power control, sub-carrier selection, load balancing, etc.

  Using a similar approach, we currently investigate MAC layer scheduling algorithms and power control protocols for MANETs and their vehicular variants called VANETs. We concentrate on cross layer optimizations allowing one to maximize the transport capacity of multihop MANETs. A recent example within this class of problems is that of opportunistic routing for MANETs. Our main quantitative results concern one-hop analysis as well as scaling laws for end-to-end delays on long routes. This last question is treated studying an appropriate first passage percolation problem on a new class of random graphs called *space-time SINR graphs*.
- **Theory of network dynamics.** TREC is also pursuing the elaboration of a stochastic network calculus, that would allow the analysis of network dynamics by algebraic methods. The mathematical tools are those of discrete event dynamical systems: semi-rings, ergodic theory, perfect simulation, stochastic comparison, inverse problems, large deviations, etc.
- **Economics of networks** The premise this relatively new direction of research, developed jointly with Jean Bolot (SPRINT) 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 and derived a model showing that network externalities and misaligned incentives are responsible for a low investment in security measures. We then analyzed the possible impact of insurance.

- **The development of mathematical tools based on stochastic geometry and random geometric graphs** Classical Stochastic Geometry. 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/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 for stochastic processes taking place on such graphs. Thereby, we were able to analyze an iterative message passing algorithm for the random assignement problem and to characterize its performance. Likewise, we made a sensitivity analysis of such processes and computed the corresponding scaling exponents (for a dynamic programming optimization problem). We also derived analytic formula for the spectrum of the adjacency matrix of diluted random graphs.

4. Application Domains

4.1. Application Domains

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

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

We interact on these questions with the following industrial partners: Thomson (probing), Alcatel (wireline access with Antwerp and wireless access with Villarceaux) and Sprint (Internet probing and wireless access). We also have some point to point interactions with researchers of France Télécom on wireless cellular networks.

5. Software

5.1. SERT, UTRANDIM

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

UTRANDIM is a continuation of SERT (Spatial Erlang for Real Time services), a Software 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 6.1.1. The approach is constantly developed and enriched. It is now included in UTRANDIM, a current dimensioning tool of Orange Corporate for UMTS and LTE networks.

5.2. Layered Coding Control

Participants: François Baccelli, Danny De Vleeschauwer [Alcatel-Lucent], Dohy Hong [N2NSoft].

TREC participated in the design of a software tool developed by N2NSoft for the optimal control of the diffusion of video on demand in a large DSL access network. The setting is that of layered coding where a controlled degradation of the quality of the video streams may be preferred to the rejection of customers. Various schemes are implemented in the software tool including a scheme based on Markov decision theory. This work was part of a research contract of Alcatel-Lucent involving TREC and N2NSoft.

6. New Results

6.1. Design and Performance Analysis of Wireless Networks

Participants: François Baccelli, Bartek Błaszczyszyn, Chung Shue Chen, Mir Omid Haji Mirsadeghi, Frédéric Morlot, Tien Viet Nguyen, Van Minh Nguyen.

This axis concerns 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 concern 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.

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 Sprint. We also have personal collaborations with two researchers of Orange Labs.

6.1.1.1. Dimensioning of OFDMA/LTE networks.

Building upon the scalable admission and congestion control schemes developed in [38], [34], which allow for an exact representation of the geometry of interference in networks, in collaboration with M.K. Karray [Orange Labs], we continue developing a *comprehensive approach to the performance evaluation of cellular networks*. This approach, that resulted in three patents filed by INRIA and FT, is used by Orange. Some of our methods were in particular integrated to Orange's dimensioning tool (initially SERT, now *UTRANDIM*).

This year, the main focus was on the extension of our approach to cellular networks implementing Orthogonal Frequency-Division Multiple Access (OFDMA). The recent interest in OFDMA comes from the fact that it is used in the mobility mode of IEEE 802.16 WirelessMAN Air Interface standard, commonly referred to as WiMAX and OFDMA is currently a working assumption in 3GPP Long Term Evolution (LTE) downlink. Also, OFDMA is the candidate access method for the IEEE 802.22 Wireless Regional Area Networks. It is the context of LTE cellular networks that we have primarily on mind. However, our approach applies to other OFDMA downlink scenarios as well.

The primary objective is to build a *dimensioning method* for the radio part of the downlink in wireless cellular OFDMA networks, i.e.; a method allowing one to evaluate what is the minimal density of base stations assuring a given quality of service (QoS) for a given traffic demand per surface unit.

In [14] we use information theory to characterize the bit-rate in the channel from a base station to its mobile. It depends on the power and bandwidth allocated to this mobile. Then, we describe the resource (power and bandwidth) allocation problem and characterize feasible configurations of bit-rates of all users. As the key element, we propose some sufficient condition (in a multi-Erlang form) for a given configuration of bit-rates to be feasible. Finally, we consider an Erlang loss model, in which streaming arrivals whose admission would lead to the violation of this sufficient condition are blocked and lost. We evaluate the minimal density of base stations assuring acceptable blocking probabilities for a streaming traffic with a given load per surface unit. We validate this approach by comparison of the blocking probabilities to those simulated in a similar model in which the admission control is based on the original feasibility property (instead of its sufficient condition). Our sufficient bit-rate feasibility condition can also be used to dimension the network for elastic traffic.

In [15] we account for the effect of fading in the above approach. The main practical results of this work are the following. Firstly, for the non-opportunistic sub-channel allocation, we evaluate the degradation due to fading compared to AWGN (that is, a decrease of throughput of at least 13%). Secondly, we evaluate the gain induced by the opportunistic allocation. In particular, when the traffic demand per cell exceeds some value (about 2.5 Mbps in our example), the gain induced by opportunism compensates the degradation induced by fading compared to AWGN.

6.1.1.2. Self-Optimization of User Association and Power.

In the submitted paper [42] we develop mathematical and algorithmic tools for the self-optimization of mobile cellular networks. Scalable algorithms which are based on local measurements and do not require heavy coordination among the wireless devices are proposed. We focus on the optimization of power and of user association. The method is applicable to both joint and separate optimizations. The global utility minimized is linked to potential delay. The distributed algorithm adaptively tunes the system parameters and achieves global optimality by measuring SINR and interference. The algorithms are built on Gibbs' sampler, which offers a unified framework that can easily be reused for different purposes. This work is part of the joint laboratory with Alcatel-Lucent and was presented by C. Chen at the joint laboratory days in October.

6.1.1.3. Self-Optimization of Neighbour Cell List.

The configuration of the neighbour cell list (NCL) has an important impact on the number of dropped calls in cellular networks. In [55] a method for optimizing NCLs is presented. It consists of an initialization using a self-configuration phase, followed by a self-optimization phase that further refines the NCL based on measurements provided by mobile stations during the network operation. Algorithms for both initial self-configuration, and ongoing self-optimization are presented. The performance of the proposed methods is evaluated for different user speeds and different NCL sizes. In addition, the convergence speed of the proposed self-optimization method is evaluated.

6.1.1.4. Extremal Signal Quality in Small Cell Networks

In the papers [53], [50], we investigate two critical issues pertaining to small cell networks: best signal quality and user mobility management. We show that, in dense small cell networks, the extremal signal strength distribution tends, after renormalization, to a Gumbel distribution and that it is asymptotically independent of the total interference. Besides, we propose a simple random cell scanning scheme. We establish an analytical model to find the optimal number of cells to be scanned.

6.1.1.5. Best SINRs in Macro Cellular Networks

The distribution of the maximum of the SINRs, Y_S, received from a cell set S is useful for many problems in cellular networks. By modelling the interference field as a shot noise process, in an ongoing work [54] we could analyze the joint distribution of the interference and the maximum of the signal strengths, and deduce from this the distribution of Y_S. This can in particular be used to determine NCL sizes which minimize the real-time call dropping rate and maximize the user data throughput in macro cellular networks.

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, in collaboration with Paul Mühlethaler [INRIA HIPERCOM], we mainly worked on the analysis of MAC and routing protocols in multi-hop MANETS.

6.1.2.1. Opportunistic Aloha for MANETS.

Spatial Aloha is probably the simplest medium access protocol to be used in a large mobile ad hoc network: Each station tosses a coin independently of everything else and accesses the channel if it gets heads. In a network where stations are randomly and homogeneously located in a plane, there is a way to tune the bias of the coin so as to obtain the best possible compromise between spatial reuse and per transmitter throughput. In the paper [5] that complements [36] we showed how to address this questions using stochastic geometry and more precisely Poisson shot noise field theory. The theory that is developed is fully computational and leads to new closed form expressions for various kinds of spatial averages (like e.g. outage, throughput or transport). It also allows one to derive general scaling laws that hold for general fading assumptions. We exemplified its flexibility by analyzing a natural variant of Spatial Aloha which we call Opportunistic Aloha and which consists in replacing the coin tossing by an evaluation of the quality of the channel of each station to its receiver and a selection of the stations with good channel (e.g. fading) conditions. We showed how to adapt the general machinery to this variant and how to optimize and implement it. We also showed that when properly tuned, Opportunistic Aloha very significantly outperforms Spatial Aloha, with e.g. a mean throughput per unit area twice higher for Rayleigh fading scenarios with typical parameters.

6.1.2.2. Comparison of Slotted to Non-slotted Aloha for MANETS

In [29] we propose two analytically tractable stochastic models of non-slotted Aloha for MANETs: a first model assumes a static pattern of nodes while the other assumes that the pattern of nodes varies over time. Both models feature transmitters randomly located in the Euclidean plane, according to a Poisson point process with the receivers randomly located at a fixed distance from the transmitters. We concentrate on the so-called outage scenario, where a successful transmission requires a Signal-to-Interference-and-Noise Ratio (SINR) larger than a given threshold. With Rayleigh fading and the SINR averaged over the duration of the packet transmission, both models lead to closed form expressions for the probability of successful transmission. We show an excellent matching of these results with simulations. Using our models we compare the performances of non-slotted Aloha to the previously studied slotted Aloha. We observe that when the path loss is not very strong, both models, when appropriately optimized, exhibit similar performance. For stronger path loss, non-slotted Aloha performs worse than slotted Aloha. However when the path loss exponent is equal to 4 its density of successfully received packets is still 75% of that in the slotted scheme. This is still much more than the 50% predicted by the well-known analysis where simultaneous transmissions are never successful. Moreover, in any path loss scenario, both schemes exhibit the same energy efficiency.

6.1.2.3. A New Phase Transitions for Local Delays in MANETs

Consider again a slotted version of Aloha for MANETS. As above, our model features transmitters randomly located in the Euclidean plane, according to a Poisson point process and a set of receivers representing the next-hop from every transmitter. We concentrate on the so-called outage scenario, where a successful transmission requires a SINR larger than some threshold. In [24] we analyze the local delays in such a network, namely the number of times slots required for nodes to transmit a packet to their prescribed next-hop receivers. The analysis depends very much on the receiver scenario and on the variability of the fading. In most cases, each node has finite-mean geometric random delay and thus a positive next hop throughput. However, the spatial (or large population) averaging of these individual finite mean-delays leads to infinite values in several practical cases, including the Rayleigh fading and positive thermal noise case. In some cases it exhibits an interesting phase transition phenomenon where the spatial average is finite when certain model parameters (receiver distance, thermal noise, Aloha medium access probability) are below a threshold and infinite above. To the best of our knowledge, this phenomenon, has not been discussed in the literature. We comment on the relationships between the above facts and the heavy tails found in the so-called "RESTART" algorithm. We argue that the spatial average of the mean local delays is infinite primarily because of the outage logic, where one transmits full packets at time slots when the receiver is covered at the required SINR and where one wastes all the other time slots. This results in the "RESTART" mechanism, which in turn explains why we have infinite spatial average. Adaptive coding offers another nice way of breaking the outage/RESTART logic. We show examples where the average delays are finite in the adaptive coding case, whereas they are infinite in the outage case.

6.1.2.4. Opportunistic Routing in MANETs.

In classical routing strategies for wireless ad-hoc (mobile or mesh) networks packets are transmitted on a pre-defined route that is usually obtained by a shortest path routing protocol. In [6] we review some recent ideas from [33], [35] concerning a new routing technique which is *opportunistic* in the sense that each packet at each hop on its (specific) route from an origin to a destination takes advantage of the actual pattern of nodes that captured its recent (re)transmission in order to choose the next relay. The paper focuses both on the distributed algorithms allowing such a routing technique to work and on the evaluation of the gain in performance it brings compared to classical mechanisms. On the algorithmic side, we show that it is possible to implement this opportunistic technique in such a way that the current transmitter of a given packet does not need to know its next relay a priori, but the nodes that capture this transmission (if any) perform a *self selection* procedure to chose the packet relay node and acknowledge the transmitter. We also show that his routing technique works well with various medium access protocols (such as Aloha, CSMA, TDMA) Finally, we show that the above relay self selection procedure can be optimized in the sense that it is the node that optimizes some given utility criterion (e.g. minimize the remaining distance to the final destination) which is chosen as the relay. The performance evaluation part is based on stochastic geometry and combines simulation a analytical models. The main result is that such opportunistic schemes very significantly outperform classical routing schemes when properly optimized and provided at least a small number of nodes in the network know their geographical positions exactly.

Mathematical analysis of asymptotic properties of opportunistic routing on large distances (when the Euclidean distance between the source and destination node tends to infinity) reviles the following surprising negative result: Under Poisson assumption for the repartition of nodes and some natural assumptions on the wireless channels, the mean delay per unit of distance is infinite. The main positive result states that when adding a periodic node infrastructure of arbitrarily small intensity to the Poisson point process, this “delay rate” is positive and finite (see Section 6.4.4.3 for more details).

6.1.2.5. Cognitive Radio

In [52] we propose a probabilistic model based on stochastic geometry to analyze cognitive radio in a mobile ad hoc network using carrier sensing multiple access. Analytical results are derived on the impact of the interaction between primary and secondary users on their medium access probability, coverage probability and throughput. These results give insight on the guarantees which can be offered to primary users and more generally on the possibilities offered by cognitive radio to improve the effectiveness of spectrum utilization in such networks.

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. Optimizing Throughput in Linear VANETs.

In [16] we adapted the stochastic geometry framework previously worked out for planar MANETs to propose two models of point to point traffic for Aloha-based linear VANETs. The first one uses a SINR capture condition to qualify a successful transmission, while the second one express the transmission throughput as a function of SINR using Shannon’s law. Assuming a Poisson repartition of vehicles, a power-law mean path-loss and a Raleigh fading, we derive explicit formulas for the probability of a successful transmission on a given distance and the mean throughput, respectively. Furthermore, we optimize two quantities directly linked to the achievable network throughput: the mean density of packet progress and the mean density of information transport. This is realized by tuning the communication range and the probability of channel access. We also present numerical examples and study the impact of the thermal noise on the optimal tuning of network parameters. The mathematical tools for its analysis are borrowed from [36] and [5].

6.1.3.2. Performance of VANETs under Different Attenuation and Fading Conditions

In [17] we perform a more massive simulation study of the performance of current wireless MAC protocols unsuitable for use in VANETs without modifications. These protocols can be tuned to design a VANET with optimal network throughput. We study two popular MAC schemes (Aloha and CSMA) in a linear VANET and analyze them in terms of density of progress of the transmissions under different attenuation and fading conditions. The results show how network performance deteriorates with changes in the conditions and how we can improve it by tuning the MAC protocols. The results presented in this paper can be useful for the design and optimal tuning of VANETs in varying network conditions (attenuation, fading and noise).

6.1.4. Generic Wireless Networks

6.1.4.1. Power Control in Wireless Networks

In [43], we study the weighted sum rate maximization problem in wireless networks consisting of multiple source-destination pairs. The optimization problem is in general non-convex and there are multiple local maxima. A simple iterative power control algorithm for the system optimization is presented. Convergence property holds. By comparing against benchmark problem instances and two other algorithms, we show by simulation that if we choose the initial power allocation randomly, the proposed algorithm converges to the global maximum with very high probability. Performance comparison under different network densities has also indicated its effectiveness. Two variants of the design are offered for different needs. Besides, some optimal properties under special cases are developed.

6.1.4.2. Conflict-Avoiding Codes

Conflict-avoiding codes are used in the multiple access collision channel without feedback. The number of codewords in a conflict-avoiding code is the number of potential users that can be supported in the system. In [43], a new upper bound on the size of conflict-avoiding codes is proved. This upper bound is general in the sense that it is applicable to all code lengths and all Hamming weights. Several existing constructions for conflict-avoiding codes, which are known to be optimal for Hamming weights equal to four and five, are shown to be optimal for all Hamming weights in general.

6.1.4.3. User Mobility Models

In [49], we analyze phenomena related to user clumps and hot spots occurring in mobile networks at the occasion of large urban mass gatherings like the *Fête de la Musique* in French cities. Our analysis is based on observations made on mobility traces of GSM users in several large cities. Classical mobility models, such as the random waypoint, do not allow one to represent the observed dynamics of clumps in a proper manner. This motivates the introduction and the mathematical analysis of a new interaction-based mobility model. This model is shown to allow one to describe the dynamics of clumps and in particular to predict key phenomena such as the building of hot spots and the scattering between hot spots, which play a key role in the engineering of wireless networks during such events. We show how to obtain the main parameters of this model from simple communication activity measurements and we illustrate this calibration process on real cases.

6.2. Network Dynamics

Participants: François Baccelli, Ana Bušić, Giovanna Carofiglio, Sergey Foss, Bruno Kauffmann, Marc Lelarge.

This traditional research topic of TREC has several new threads like perfect simulation, active probing or Markov decision.

6.2.1. Queueing Theory and Active Probing

6.2.1.1. Inverse Problems.

Active probing began by measuring end-to-end path metrics, such as delay and loss, in a direct measurement process which did not require inference of internal network parameters. The field has since progressed to measuring network metrics, from link capacities to available bandwidth and cross traffic itself, which reach deeper and deeper into the network and require increasingly complex inversion methodologies. In [7], we formulate this line of thought as a set of inverse problems in queueing theory. Queueing theory is typically concerned with the solution of direct problems, where the trajectory of the queueing system, and laws thereof, are derived based on a complete specification of the system, its inputs and initial conditions. Inverse problems aim to deduce unknown parameters of the system based on partially observed trajectories. We provide a general definition of the inverse problems in this class and map out the key variants: the analytical methods, the statistical methods and the design of experiments. We also show how this inverse problem viewpoint translates to the design of concrete Internet probing applications.

6.2.1.2. *Internet Tomography.*

Most active probing techniques suffer of the “Bottleneck” limitation: all characteristics of the path after the bottleneck link are erased and unreachable. we are currently investigating a new tomography technique, based on the measurement of the fluctuations of point-to-point end-to-end delays, and allowing one to get insight on the residual available bandwidth along the whole path. For this, we combine classical queueing theory models with statistical analysis to obtain estimators of residual bandwidth on all links of the path. These estimators are proved to be tractable, consistent and efficient. In [8] we evaluate their performance with simulation and trace-based experiments.

Lately this method has been generalized in [56] to a probing multicast tree instead of a single path

6.2.2. Perfect Simulation

Perfect simulation, introduced by Propp and Wilson in 1996, is a simulation 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 end state is the same for all trajectories, then the chain has coupled and the end state has the stationary distribution of the Markov chain. Otherwise, the simulations are started further in the past. The complexity of the algorithm depends on the cardinality of the state space, which is prohibitive for most applications. This simulation technique becomes efficient if the Markov chain is monotone, as the monotonicity allows to consider only the extremal trajectories of the system. In the non-monotone case, it is possible to avoid generating all the trajectories by considering bounding processes (Hubert, 2004). The construction of these bounding processes is model-dependent and in general not straightforward. In a recent work [39] we proposed an algorithm to construct bounding processes, called envelopes, for the case of a finite Markov chain with a lattice structure. We show that this algorithm is efficient for some classes of non-monotone queueing networks, such as networks of queues with batch arrivals, queues with fork and join nodes and/or with negative customers.

6.2.2.1. *Perfect Sampling of Piece-wise Space Homogeneous Markov Chains.*

In an ongoing work with B. Gaujal [INRIA Rhône-Alpes], F. Pin [ENS Paris] and J.-M. Vincent [Université Joseph Fourier], we are extending these results to a more general framework of piece-wise space homogeneous Markov chains (each event divides the state space into a few zones and the transition of the event is constant within each zone).

6.2.2.2. *Probabilistic cellular automata, invariant measures, and perfect simulation.*

Cellular automata were first introduced as deterministic functions $F : \mathcal{A}^E \to \mathcal{A}^E$, were $\mathcal{A}$ is a finite alphabet, and E a discrete space ($E = \mathbb{Z}^d$ or $\mathbb{Z}/n\mathbb{Z}$). Their particularity is to be characterized by a local transition function $f : \mathcal{A}^V \to \mathcal{A}$ for some finite neighborhood $V \subset E$, through the relation $(F(x))_k = f((x_{k+i})_{i \in V})$. In an ongoing work with J. Mairesse [LIAFA, CNRS and Université Paris 7] and I. Marcovici [ENS Lyon], we consider probabilistic cellular automata (PCA), which are defined by a local function $f : \mathcal{A}^V \to (M)(\mathcal{A})$, where $(M)(\mathcal{A})$ denotes the set of probability measures on $\mathcal{A}$. We study some properties of their invariant measures, and propose an algorithm allowing for perfect sampling of the stationary distribution of an ergodic PCA that is an extension of the envelope algorithm in [39].

6.2.3. Markov reward and Markov decision processes

Numerical methods for solving Markov chains are in general inefficient if the state space of the chain is very large (or infinite) and lacking a simple repeating structure. An alternative to solving such chains is to construct models that are simple to analyze and that provide bounds for a reward function of interest. In a recent work [28] 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 on the original system. Redirecting sets of transitions is based on an extension of precedence relations to sets of states (van Houtum et al. 1998), and allows to design more accurate bounds (ex: bounds having the same mean behavior). We show that our method is compatible with strong aggregation of Markov chains; thus we can obtain bounds for the initial chain by analyzing a much smaller chain. We apply the precedence relations on set of states combined with aggregation to prove the bounds of order fill rates for an inventory system of service tools with joint demands/returns. We are currently extending these results to Markov decision processes.

In an ongoing work with I.M. H. Vliegen [Technische Universiteit Eindhoven, The Netherlands] and A. Scheller-Wolf [Carnegie Mellon University, USA], we apply these results in an optimization problem of base stock levels for service tools inventory. The first results of this work were published as a part of the PhD thesis of I. Vliegen (defended in November 2009) [57].

6.2.4. Stochastic Stability

6.2.4.1. Bipartite Matching Queueing Model

In an ongoing work with V. Gupta [Carnegie Mellon University, USA] and J. Mairesse Ana Bušić studies the bipartite matching model of customers and servers is a queueing model introduced by Caldentey, Kaplan and Weiss (Adv. in Appl. Probab., 2009). Let C and S be the sets of customer and server classes. At each time step, a pair of customer and server arrive according to a joint probability measure μ. Also, a pair of *matched* customer and server, if there exists any, departs from the system. *Authorized matchings* are given by a fixed bipartite graph $G = (C, S, E)$, where $E \subset C \times S$. The evolution of the model can be described by a discrete time Markov chain, where the state of the chain is given by two equal-length words of unmatched customers and servers. The stability properties are studied under various BF (Buffer First) matching policies, i.e. policies with priority given to customers/servers that are already present in the buffer. It includes the following policies: FIFO, priorities, MLQ (Match the Longest Queue), or MSQ (Match the Shortest Queue). Assume that the model cannot be decomposed into two independent submodels. Necessary stability conditions are then given by:

$$NCond: \quad \begin{cases} \mu(U, S) < \mu(C, S(U)), \ U \subsetneq C \\ \mu(C, V) < \mu(C(V), S), \ V \subsetneq S \end{cases}$$

where $S(U)$ denotes the servers that can be matched with customers in U (and $C(V)$ is defined dually).

The notion of *extremal facet* is introduced. For models with only extremal facets, the stability region is maximal for any BF policy, i.e. the conditions $NCond$ are also sufficient. For models with non-extremal facets, the situation is more intricate. The MLQ policy has a maximal stability region. In the case of a tree, there is a static priority policy that has maximal stability region.

6.2.4.2. Spatial Queues

In a joint work with S. Foss [Heriot–Watt University, UK] [37], we consider a queue where the server is the Euclidean space, the customers are random closed sets of the Euclidean space arriving according to a Poisson rain and where the discipline is a hard exclusion rule: no two intersecting random closed sets can be served at the same time. We use the max plus algebra and Lyapunov exponents to show that under first come first serve assumptions, this queue is stable for a sufficiently small arrival intensity. We also discuss the percolation properties of the stationary regime of the random closed sets in the queue.

6.2.5. Flow and Congestion Control

The main topics covered in 2009 concern transport equations for Scalable TCP and for Split TCP.

6.2.5.1. Split TCP

The idea of Split TCP is to replace a multihop, end-to-end TCP connection by a cascade of shorter TCP connections using intermediate nodes as proxies, thus achieving higher throughput. In the model that we developed with G. Carofiglio [Bell Laboratories, Alcatel–Lucent] and S. Foss, we consider two long-lived TCP-Reno flows traversing two links with different medium characteristics in cascade. A buffer at the end of the first link prevents the loss of packets that cannot be immediately forwarded on the second link by storing them temporarily. The target of our study is the characterization of the TCP throughput on both links as well as the buffer occupancy. In [22] we establish the partial differential equations for throughput dynamics jointly with that of buffer occupancy in the proxy, we determine the stability conditions by exploiting some intrinsic monotonicity and continuity properties of the system and we derive tail asymptotics for buffer occupancy in the proxy and end-to-end delays.

6.2.5.2. Scalable TCP

The unsatisfactory performance of TCP in high speed wide area networks has led to several versions of TCP–like HighSpeed TCP, Fast TCP, Scalable TCP or CUBIC, all aimed at speeding up the window update algorithm. In a joint work with G. Carifiglio [13], we focus on Scalable TCP which belongs to the class of Multiplicative Increase Multiplicative Decrease congestion control protocols. We present a new stochastic model for the evolution of the instantaneous throughput of a single STCP flow in the Congestion Avoidance phase, under the assumption of a constant per-packet loss probability. This model allows one to derive several closed-form expressions for the key stationary distributions associated with this protocol: we characterize the throughput obtained by the flow, the time separating Multiplicative Decrease events, the number of bits transmitted over certain time intervals and the size of rate decrease. Several applications leveraging these closed form expressions are considered with a particular emphasis on QoS guarantees in the context of dimensioning.

6.2.6. Rare Events in Stochastic Networks

In [11], we analyze the behavior of Generalized Processor Sharing (GPS) queues with heavy-tailed service times. We compute the exact tail asymptotics of the stationary workload of an individual class and give new conditions for reduced-load equivalence and induced burstiness to hold. We also show that both phenomena can occur simultaneously. Our proofs rely on the single big event theorem and new fluid limits obtained for the GPS system that can be of interest by themselves.

6.3. Economics of Networks

Participant: Marc Lelarge.

6.3.1. Analysis of Security Investments in Networks

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. Our goal in this paper is to model and quantify the impact of such externalities on the investment in security features in a network. In [19], we study a network of interconnected agents, which are subject to epidemic risks such as those caused by propagating viruses and worms. Each agent can decide whether or not to invest some amount to self-protect and deploy security solutions which decreases the probability of contagion. Borrowing ideas from random graphs theory, we solve explicitly this "micro"-model and compute the fulfilled expectations equilibria. We are able to compute the network externalities as a function of the parameters of the epidemic. We show that the network externalities have a public part and a private one. As a result of this separation, some counter-intuitive phenomena can occur: there are situations where the incentive to invest in self-protection decreases as the fraction of the population investing in self-protection increases. In a situation where the protection is strong and ensures that the protected agent cannot be harmed by the decision of others, we show that the situation is similar to a free-rider problem. In a situation where the protection is weaker, then we show that the network can exhibit critical mass. We also look at interaction with the security supplier. In the case where security is provided by a monopolist, we show that the monopolist is taking advantage of these positive network externalities by providing a low quality protection.

6.3.2. Cyber Insurance as an Incentive for Internet Security

Entities in the Internet, ranging from individuals and enterprises to service providers, face a broad range of epidemic risks such as worms, viruses, and botnet-driven attacks. Those risks are interdependent risks, which means that the decision by an entity to invest in security and self-protect affects the risk faced by others (for example, the risk faced by an individual decreases when its providers increases its investments in security). As a result of this, entities tend to invest too little in self-protection, relative to the socially efficient level, by ignoring benefits conferred on by others.

In a joint work with Jean Bolot [Sprint ATL, USA] [18], we consider the problem of designing incentives to entities in the Internet so that they invest at a socially efficient level. In particular, we find that insurance is a powerful incentive mechanism which pushes agents to invest in self-protection. Thus, insurance increases the level of self-protection, and therefore the level of security, in the Internet. As a result, we believe that insurance should be considered as an important component of risk management in the Internet.

6.4. Point Processes, Stochastic Geometry and Random Geometric Graphs

Participants: François Baccelli, Pierre Brémaud, Bartek Błaszczyszyn, Yogeshwaran Dhandapani, Mir Omid Haji Mirsadeghi, Justin Salez.

6.4.1. Book on Stochastic Geometry and Wireless Networks

TREC is actively working on a book project focused on the use of the stochastic geometry framework for the modeling of wireless communications.

Stochastic geometry is a rich branch of applied probability which allows to study random phenomenons on the plane or in higher dimension. It is intrinsically related to the theory of point processes. Initially its development was stimulated by applications to biology, astronomy and material sciences. Nowadays, it is also used in image analysis. During the 03-08 period, we contributed to proving that it could also be of use to analyze wireless communication networks. The reason for this is that the geometry of the location of mobiles and/or base stations plays a key role since it determines the signal to interference ratio for each potential channel and hence the possibility of establishing simultaneously some set of communications at a given bit rate.

Stochastic geometry provides a natural way of defining (and computing) macroscopic properties of wireless networks, by some averaging over all potential geometrical patterns for e.g. the mobiles. Its role is hence similar to that played by the theory of point processes on the real line in the classical queueing theory. The methodology was initiated in [32], [36] and it was further developed through several papers including [40], [51], [41], [5], [6].

The two-volume book [1], [2] that will appear in the series *Foundations and Trends in Networking* (NOW Publishers; http://www.nowpublishers.com/product.aspx?product=NET&doi=1300000006, http://www.nowpublishers.com/product.aspx?product=NET&doi=1300000026) will survey these papers and more recent results [25], [24] obtained by this approach for analyzing key properties of wireless networks such as coverage or connectivity, and for evaluating the performance of a variety of protocols used in this context such as medium access control or routing.

More precisely, Volume I provides a concise introduction to relevant models of stochastic geometry, such as spatial shot-noise processes, coverage processes and random tessellations, and to variants of these basic models which incorporate information theoretic notions, such as signal to noise ratio.

Volume II shows how these space-time averages can be used to analyze and optimize the medium access control and routing protocols of interest in large wireless communication networks. This is based on both qualitative and quantitative results. The most important qualitative results are in terms of phase transitions for infinite population models. Quantitative results leverage closed form expressions for the key network performance characteristics.

The monograph provides a comprehensive and unified methodology for wireless network design and it gives a direct access to an emerging and fast growing branch of stochastic modeling.

6.4.2. Research on Stochastic Comparison of Random Measures and Point Processes

Stochastic geometric models of wireless networks have in general been investigated under Poissonian setting (see [32], [36]). The first aim of the PhD thesis of Yogeshwaran D. is to study certain performance measures of wireless networks using stochastic geometric tools in the non-Poissonian setting. Due to the difficulty in obtaining closed-form expressions for various performance measures in non-Poissonian settings (see [58]), we attempted a qualitative study of the performance measures.

6.4.2.1. Directionally Convex Ordering

Directionally convex (dcx) ordering is a tool for comparison of dependence structure of random vectors that also takes into account the variability of the marginal distributions. When extended to random fields it concerns comparison of all finite dimensional distributions. In [9], viewing locally finite measures as non-negative fields of measure-values indexed by the bounded Borel subsets of the space,

we formulate and study the dcx ordering of random measures on locally compact spaces. We show that the dcx order is preserved under some of the natural operations considered on random measures and point processes, such as deterministic displacement of points, independent superposition and thinning as well as independent, identically distributed marking. Further operations such as position dependent marking and displacement of points though do not preserve the dcx order on all point processes, are shown to preserve the order on Cox point processes. We also examine the impact of dcx order on the second moment properties, in particular on clustering and on Palm distributions. Comparisons of Ripley's functions, pair correlation functions as well as examples seem to indicate that point processes higher in dcx order cluster more. As the main result, we show that non-negative integral shot-noise fields with respect to dcx ordered random measures inherit this ordering from the measures. Numerous applications of this result are shown, in particular to comparison of various Cox processes and some performance measures of wireless networks, in both of which shot-noise fields appear as key ingredients.

6.4.2.2. Percolation and Directionally Convex Ordering of Point Processes and Random Fields

Heuristics indicate that clustering of a point process negatively impacts the percolation of the related continuum percolation model, called also the Boolean model. In in current work in progress we move towards a formal statement of this heuristic. Namely, we consider some critical radii for continuum percolation model and show that these are greater for Cox point processes, which are greater in the so called dcx order. This integral order has previously been shown (see [9]) as suitable for comparison of dependence structure and clustering properties of point processes. Extensions to general point processes as well as comparison of critical levels for percolation of the level-sets of random fields are also discussed. Further, we give examples of point processes whose Boolean models percolate better than Poisson Boolean models.

6.4.3. Information Theory and Stochastic Geometry

In a joint work with Venkat Anantharam (UC Berkeley) [31], a new class of problems was defined in the theory of Euclidean point processes, motivated by the study of the error exponent (reliability function) for additive noise channels in Information Theory. Each point of the point process is seen as a codeword and the additive noise as a random displacement from this point. Decoding is successful when the displacement of a point falls in the Voronoi cell of this point. For a wide class of point processes that have incarnations in all dimensions, there is a 0–1 law on the probability of successful decoding when dimension goes to infinity. This can be seen as an extension of Shannon's capacity theorem and error exponents can also be defined within this context. For the case of Gaussian noise this approach gives an interesting perspective on the Poltyrev exponent. It also suggests an approach to attack the long standing gap between the best known lower and upper bounds on the reliability function of the traditional AWGN channel, using techniques from point process theory. A new paper is under preparation with results on error exponents for stationary and ergodic noise.

6.4.4. Random Geometric Graphs

Random Geometric Graphs (RGG) have played an important role in providing a framework for modeling in wireless communication, starting with the pioneering work on connectivity by Gilbert (1961); [46]. Vertices or points of the graphs represent communicating entities such as base stations. These vertices are assumed to be distributed in space randomly according to some point process, typically a Poisson point process. En edge between two points means that the communicating entities able to communicate with each other. In the classical model an edge exists between any two pair of nodes if the distance between them is less than some critical threshold. A variant of this classical model that exhibits the union of the coverage regions of all nodes is also referred to in stochastic geometry as the Boolean model. In the following, more fundamental works, we study some variants and extensions of the classical models, more or less related to wireless communication networks.

6.4.4.1. *AB Random Geometric Graphs*

We investigate 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 study is a generalization to the continuum of the AB percolation model on discrete lattices. We show existence of AB percolation for all $d \geq 2$, and derive bounds for a critical intensity. For AB random geometric graphs, we derive a weak law result for the largest nearest neighbor distance and almost sure asymptotic bounds for the connectivity threshold. This submitted work can be found in [47].

6.4.4.2. *First Passage Percolation Model for Delay Tolerant Networks*

Delay Tolerant Networks, in the simplest terms, are networks that take into account the time-delay in the transmission of information along a network. First passage percolation models have been found to be useful for study of transmission of information along networks. We consider spatial first passage percolation on stationary graphs constructed on point processes with delayed propagation of the information at the vertices of the graph. Depending on the manner of the time-delay, one can obtain various models. The time for propagation of information along networks in such models do not possess the sub-additive property, a key component in the study of first passage percolation models. This is a work in progress.

6.4.4.3. *Optimal Paths on Time-Space SINR Graphs*

The following mathematical formalism proposed in [35] is useful when studying macroscopic properties of routing in MANETs, and in particular these produced by opportunistic routing in the sense described in Section 6.1.2. One can model the users of a mobile as points of a stochastic point process where each node can be a transmitter or receiver in each time step. The SINR graph is a geometric graph where the nodes are the points of a point process and an edge is present between a transmitter and a receiver if the SINR at the receiver is above a certain threshold. Due to fluctuations in propagation and MAC, these edges vary in time. In order to account for this fact, in [25] we introduce and analyze SINR graphs which have space and a time dimension. The spatial aspect originates from the random locations of the network nodes in the Euclidean plane. The time aspect stems from the random transmission policy followed by each network node and from the time variations of the wireless channel characteristics. The combination of these random space and time aspects leads to fluctuations of the SINR experienced by the wireless channels, which in turn determine the progression of packets in space and time in such a network.

The paper [25] studies optimal paths in such wireless networks in terms of first passage percolation on this random graph. We establish both "positive" and "negative" results on the associated the percolation delay rate (delay per unit of Euclidean distance called in the classical terminology time constant). 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.

6.4.5. *Ergodicity of a Stress-Release-Point-Process Seismic Model with Aftershocks*

The times of occurrence of earthquakes in a given area of seismic activity form a simple point process N on the real line, where $N((a,b])$ is the number of shocks in the time interval $(a,b]$. The dynamics governing the process can be expressed by the stochastic intensity $\lambda(t)$. In the stress release model, for $t \geq 0$, $\lambda(t) = e^{X_0 + ct - \sum_{n=1}^{N((0,t])} Z_n}$, where $c > 0$ and $\{Z_n\}_{n\geq 1}$ is an i.i.d. sequence of non-negative random variables with finite expectation, whereas X_0 is some real random variable. The process $X(t) = X_0 + ct - \sum_{n=1}^{N((0,t])} Z_n$ is known to be ergodic.

Another model of interest in seismology is the Hawkes branching process, where the stochastic intensity is $\lambda(t) = \nu(t) + \int_{(0,t]} h(t-s)N(ds)$, where h is a non-negative function, called the fertility rate and ν is a non-negative integrable function. Such point process appears in the specialized literature under the name ETAS (Epidemic Type After-Shock and is used to model the aftershocks. It is well known that the corresponding process "dies out" in finite time under the condition $\int_0^\infty h(t)\,dt < 1$.

A model mixing stress release and Hawkes aftershocks is

$$\lambda(t) = e^{X_0 + ct - \sum_{n=1}^{N((0,t])} Z_n} + Y_0 e^{-\alpha t} + k \int_{(0,t]} e^{-\alpha(t-s)}\, N(ds),$$

where $\alpha > 0$. The positive constant c is the rate at which the strain builds up. If there is a shock at time t, then the strain is relieved by the quantity $Z_{N(t)}$. Each shock (primary or secondary) at time t generates aftershocks according to a Poisson process of intensity $a(s) = ke^{-\alpha(t-s)}$. In [27], we give necessary and sufficient conditions of ergodicity for this model.

6.5. Random Graphs and Combinatorial Optimization

Participants: Hamed Amini, Emilie Coupechoux, Marc Lelarge, Justin Salez.

6.5.1. Belief Propagation for the Random Assignment Problem

Belief propagation is a non-rigorous decentralized and iterative algorithmic strategy for solving complex optimization problems on huge graphs by purely-local propagation of dynamic messages along their edges. Its remarkable performance in various domains of application from statistical physics to image processing or error-correcting codes have motivated a lot of theoretical works on the crucial question of convergence of beliefs despite the cycles, and in particular the way it evolves as the size of the underlying graph grows to infinity. However, a complete and rigorous understanding of those remarkable emergence phenomena (general conditions for convergence, asymptotic speed and influence of the initialization) still misses. A new idea consists in using the topological notion of local weak convergence of random geometric graphs to define a limiting local structure as the number of vertexes grows to infinity and then replace the asymptotic study of the phenomenon by its direct analysis on the infinite graph.

This method has already allowed us to establish asymptotic convergence at constant speed for the special case of the famous optimal assignment problem, resulting in a distributed algorithm with asymptotic complexity $O(n^2)$ compared to $O(n^3)$ for the best-known exact algorithm. This is joint work with Devavrat Shah (MIT). It has been published in the Journal of Mathematics of Operations Research [12] and appeared in SODA'09 [21]. We hope this method will be easily extended to other optimization problems on tree-like graphs and will become a powerful tool in the fascinating quest for a general mathematical understanding of Belief Propagation.

6.5.2. Dynamic Programming Optimization over Random Data: the Scaling Exponent for Near-optimal Solutions

A very simple example of an algorithmic problem solvable by dynamic programming is to maximize, over $A \subseteq \{1,2,...,n\}$, the objective function $|A| - \sum_i \xi_i \mathbb{1}(i \in A, i+1 \in A)$ for given $\xi_i > 0$. This problem, with random (ξ_i), provides a test example for studying the relationship between optimal and near-optimal solutions of combinatorial optimization problems. In [4] we showed that, amongst solutions differing from the optimal solution in a small proportion δ of places, we can find near-optimal solutions whose objective function value differs from the optimum by a factor of order δ^2 but not smaller order. We conjecture this relationship holds widely in the context of dynamic programming over random data, and Monte Carlo simulations for the Kauffman-Levin NK model are consistent with the conjecture. This work is a technical contribution to a broad program initiated in Aldous-Percus (2003) of relating such scaling exponents to the algorithmic difficulty of optimization problems.

6.5.3. The rank of diluted random graphs

In [26], with Charles Bordenave (CNRS-Université de Toulouse), we investigate the rank of the adjacency matrix of large diluted random graphs: for a sequence of graphs converging locally to a tree, we give new formulas for the asymptotic of the multiplicity of the eigenvalue 0. In particular, the result depends only on the limiting tree structure, showing that the normalized rank is Çcontinuous at infinityÇ. Our work also gives a new formula for the mass at zero of the spectral measure of a Galton-Watson tree. Our techniques of proofs borrow ideas from analysis of algorithms, random matrix theory, statistical physics and analysis of Schrödinger operators on trees

6.5.4. Bootstrap Percolation in Random Networks

Bootstrap percolation model has been used in several related applications. In [23], we consider bootstrap percolation in living neural networks. Recent experimental studies of living neural networks reveal that global activation of neural networks induced by electrical stimulation can be explained using the concept of bootstrap percolation on a directed random network. The experiment consists in activating externally an initial random fraction of the neurons and observe the process of firing until its equilibrium. The final portion of neurons that are active depends in a non linear way on the initial fraction. Our main result in [23] is a theorem which enables us to find the final proportion of the fired neurons in the asymptotic case, in the case of random directed graphs with given node degrees as the model for interacting network. This gives a rigorous mathematical proof of a phenomena observed by physicists in neural networks [44].

6.5.5. Epidemics over Random Hypergraphs

In [30], we adapt the model given in [48], which is on graphs, to an equivalent on hypergraphs. For this, we generalized the result obtained by Darling and Norris in [45], which deals with the k-core of a random hypergraph. The proof of this result was the subject of the training course report (for master's degree) of E. Coupechoux [30]. Now, we are trying to deduce from this result, new results on the giant component of random hypergraphs.

6.5.6. Efficient Control of Epidemics over Random Networks

Motivated by the modeling of the spread of viruses or epidemics with coordination among agents, we introduce in [20] a new model generalizing both the basic contact model and the bootstrap percolation. We analyze this percolated threshold model when the underlying network is a random graph with fixed degree distribution. Our main results unify many results in the random graphs literature. In particular, we provide a necessary and sufficient condition under which a single node can trigger a large cascade. Then we quantify the possible impact of an attacker against a degree based vaccination and an acquaintance vaccination. We define a security metric allowing to compare the different vaccinations. The acquaintance vaccination requires no knowledge of the node degrees or any other global information and is shown to be much more efficient than the uniform vaccination in all cases.

7. Contracts and Grants with Industry

7.1. ANR CMON

Participants: François Baccelli, Bruno Kauffmann.

TREC is a partner of the 3-year ANR project called CMON, jointly with Thomson, LIP6, the INRIA project-team Planète and the community http://www.grenouille.com. 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. A postdoc (F. Benezit) was been hired through this grant from year 2010 on.

7.2. Research Grant of Thomson

Participants: François Baccelli, Bruno Kauffmann.

The collaboration with the Paris Lab of Thomson materializes into

- joint seminars and reading groups, notably the Paris-Networking series (http://www.paris-networking.org/),
- joint courses taught with L. Massoulié and A. Chaintreau,
- joint invitations of well known scientists (like e.g. V. Anantharam from Berkeley and D. Veitch from Melbourne),
- a joint patent,
- partnership in a 3-year ANR project on network measurements called *CMON* (see above).

7.3. Sprint ATL Grant

Participants: François Baccelli, Marc Lelarge.

In 2009, the interaction with the research lab of Sprint (Sprint ATL, in Burlingame, California) focused on two main topics:

- Bayesian inference to locate mobiles in cellular networks [59].
- The analysis of risks on the Internet through an interaction with J. Bolot (see Sections 6.3.1 and 6.3.2).

This collaboration resulted in several joint papers this year again.

7.4. EADS PhD fund

Participants: Bartek Błaszczyszyn, Yogeshwaran Dhandapani.

This 6 year grant started in September 06 and bears on the modeling of mobile ad hoc networks. It allowed us to hire in 2007 a PhD student, D. Yogeshwaran from IISc Bangalore. The work of D. Yogeshwaran bears on the stochastic comparison of random measures, point process and shot-noise fields.

7.5. Research Contract with Alcatel Bell "Choking of UDP traffic"

Participants: François Baccelli, Dohy Hong [N2NSoft].

In 2009 we completed the third phase of a research project with the Network Strategy Group of Alcatel Antwerp (Danny de Vleeschauwer and Koen Laevens) and with N2NSoft (Dohy Hong). This project was focused on the modeling of the interaction of a large collection of multimedia sources that join and leave and that share an access network. The main objective was the design of optimal choking policies for the transport of layer encoded video in such an access networks. The third phase of the project focused on the optimal caching strategies of video chunks within this context.

7.6. Collaboration with M. Karray of Orange-Labs

Participants: Bartek Błaszczyszyn, Francois-Xavier Klepper.

Since 2007 the collaboration with France Télécom has not been part of any formal framework. Spontaneous collaborations continue with Mohamed Karray, with whom we work on the coverage and capacity of the CDMA, UMTS and OFDM networks. This resulted in three patents. The pertinence of our approach has already been recognized by Orange Corporate. This operator uses some of our methods in its dimensioning tool *UTRANDIM*. This year the collaboration lead to two publications on the performance evaluation and dimensioning of cellular networks (see Section 6.1.1) and the co-advising of a Master Student Fran cois-Xavier Klepper.

8. Other Grants and Activities

8.1. Networks and International Working Groups

- TREC is currently a partner of the *European Network of Excellence (NoE)* called Euro-NF (http://eurongi.enst.fr/p_en_menu1_NFcommunit_396.html). This NoE, which is focused on the next generation Internet, is led by Groupement des Ecoles de Télécoms (GET) and has about 30 partners.
- F. Baccelli is a member of the working group 7.3 of IFIP.

9. Dissemination

9.1. Animation of the Scientific Community

9.1.1. TREC's seminar

the following scientists gave talks in 2009:

- France
  - Marc Lelarge from *INRIA-ENS, France*, talking on "Economics of Malware: Epidemic Risks Model, Network Externalities and Incentives" February 2009,
  - Fernando Peruani from *CEA, France*, talking on "Information spreading in dynamical networks of mobile agents"; May 2009,
  - Nicolas Gast from *INRIA, France*, talking on, "A Mean Field Approach for Optimization and Applications"; May 2009,
  - Calvin Chen from *INRIA, France*, talking on "User Unsuppressible Protocol Sequences for Collision Channels without Feedback"; May 2009,
  - Anthony P. Metcalfe from *Paris 6, France*, talking on "Universality properties of Gelfand-Tsetlin patterns"; December 2009,
  - Furcy Pin from *ENS*, talking on "Statistical Estimation of Delays in a Multicast Tree"; December 2009,
  - Bruno Kauffmann from *Inria and Paris 6*, talking on "Inverse problems in queueing networks"; December 2009,
- Europe
  - Guenter Last from *University of Karlsruhe, Germany*, talking on "Invariant transports of random measures" January 2009
  - Florence Bénézit from *EPFL, Switzerland*, talking on "Locating IP congested links with unicast probes"; March 2009,
  - Patrick Thiran from *EPFL, Switzerland*, talking on "Locating IP congested links with unicast probes", March 2009,
  - Hermann Thorisson from *University of Iceland*, talking on "Coupling and Convergence in Density and in Distribution"; June 2009,
  - Moez Draief from *Imperial College London*, talking on "Convergence Speed of Binary Interval Consensus"; September 2009,
  - Dario Maggiorini from *The University of Milano*, talking on " Network Traffic Over a Public Transportation Network: a Probabilistic Approach"; December 2009.
- Asia, Australia, Canada, USA

- Massimo Franceschetti from *University of California, San Diego, USA*, talking on “Information-theoretic and physical limits on the capacity scaling of wireless ad-hoc networks”; January 2009,
- William A. Massey from *Princeton, USA*, talking on “Dynamic Pricing to Control Loss Systems with Quality of Service Targets” and “Dynamical Queueing Systems”; January 2009,
- Ravi Mazumdar from *University of Waterloo, Canada*, talking on “Comparison theorems and the validity of heavy traffic limit distributions for stochastic networks”; May 2009,
- Vishal Misra *Columbia University, USA*, talking on “A Shapley Value approach to Internet Economics”; June 2009,
- Andrea Montanari from *Stanford University, USA*, talking on “Matrix Completion from Fewer Entries”; July 2009,
- Siu Wai Ho from *University of South Australia*, talking on “The Refinement of Two Fundamental Tools in Information Theory”; October 2009.
- D. Manjunath from *IIT Bombay, India*, talking on “Computing Functions Over Random Networks: Two New Formulations”; December 2009.

9.1.2. Miscellaneous

- TREC is a founding member of and participates to Paris-Networking (http://www.paris-networking.org/), a virtual community of researchers in networking who work in or around Paris (or visit Paris).
- M. Lelarge animates the project-team seminar http://www.di.ens.fr/~trec/.
- M. Lelarge animates the reading group on random graphs.
- B. Błaszczyszyn is a member of *Commission détachement, délégation et post-doc "sur subvention", Inria Rocquencourt*.
- P. Brémaud is a member of the editorial board of the following journals: *Journal of Applied Probability, Advances in Applied Probability, Journal of Applied Mathematics and Stochastic Analysis*;
- F. Baccelli is a member of the editorial board of the following journals: *QUESTA, Journal of Discrete Event Dynamical Systems, Mathematical Methods of Operations Research, Advances in Applied Probability*.

9.2. University Teaching

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).
- Assistant teaching in L1 and L2 courses LI102 (imperative programming and bases of algorithmic), LI105 (from chipset to the Internet) and LI218 (Initiation to task automation) by B. Kauffmann (64h in total).

Ecole Normale Supérieure

- Course on Information Theory and Coding by M. Lelarge and J. Salez,
- Math/Physics projects: Statistical mechanics of mean field disordered systems by M. Lelarge and G. Semerjian,
- Undergraduate course (master level, MMFAI) by P. Brémaud and M. Lelarge on Random Structures and Algorithms.

University of Milan, Italy A Short Course on Palm Theory for Point Processes, B. Błaszczyszyn (October 2009, 10H).

University of California Berkeley, USA A Short Course on Stochastic Geometry and Wireless Networks, F. Baccelli (September–October 2009, 8H).

9.3. Invitations and Participation in Conferences

Hamed Amini

- Participation in the following conferences:
  - Journées ALÉA, École thématique du CNRS, CIRM (Luminy, Mars 2009; http://www.liafa.jussieu.fr/~poulalho/ALEA09/).
  - Cornell Probability Summer School (Ithaca, NY, July 2009; http://www.math.cornell.edu/~durrett/CPSS2009/index.html).
  - Conference on Probabilistic Techniques in Computer Science (Barcelona, Spain, September 2009; http://www.crm.cat/ccomputer/).
  - Statistical physics, combinatorics and probability: from discrete to continuous models (Institut Henri Poincaré, Paris, September–December 2009; http://ipht.cea.fr/statcomb2009/).

François Baccelli

- Visiting Miller Professor at UC Berkeley from August to December 09;
- Scientific adviser of the “Direction Scientifique” of INRIA for communications;
- In charge of the “research chapter” of the EIT KIC proposal;
- Co-organizer of the SCS (Stochastic Processes in Communication Sciences) Programme of the Newton Institute for Mathematical Sciences to be held in Cambridge during the first semester of 2010.
- Guest co-editor of a special issue of JSAC entitled "Stochastic Geometry and Random Graphs for Wireless Networks" [10].
- Member of the program committee of IEEE Infocom’09, ITW’09;
- Co supervision of the thesis of P. Bermolen (ENST).

• Keynote lectures:
  - ValueTools’09, Pisa, Italy, October 09 (Stochastic Geometry for Wireless Networks);
  - Spaswin’09, Seoul, Korea, June 09 (Opportunistic Routing);
  - Journées de Probabilités de Poitiers, June 09 (Stochastic Geometry);
  - BCS Computer Journal Lecture, Imperial College, London, February 09 (Wireless Networks).

• Presentation at the following conferences:
  - Conference Stochastic Networks And Related Topics, Bedlewo, Poland, May 09;
  - IEEE Infocom’09, Rio de Janeiro, April 09;
  - IPAM workshop on transport equations, UCLA, April 09 (invited lecture);
  - Erlang centennial conference, Copenhagen, April 09 (invited lecture).

• Presentation at the following seminars:
  - MIT, LIDS Colloquium, December 09;
  - UC Berkeley, EECS Colloquium, December 09;

- Bell Laboratories, Murray Hill (Maths Center), June 09;
- Distinguished Lecture Series, Yonsei University, Seoul, Korea, June 09;
- Université de Lille, January 09.

Bartek Błaszczyszyn

- Member of the thesis committee of Pierre Calka (Habilitation, Université Paris 5).
- Presentation at the DGA/INRIA Seminar, (INRIA Rocquencourt, Mars 2009; http://www.inria.fr/rocquencourt/rendez-vous/manifestations/seminaire-dga-inria).
- Presentation at the conference Stochastic Networks And Related Topics (Bedlewo, Poland, May; http://www.math.uni.wroc.pl/~lorek/bedlewo2009/index.php).
- Tutorial lecture at the summer school *ResCom2009* (La Palmyre, 7-12 June 2009; http://rescom09.isae.fr).
- Presentations at the seminar of Computer Science Department, University of Milan (Milan, Italy, October 2009).

Ana Bušić

- Participation in NET-COOP (EURANDOM, Eindhoven, The Netherlands, November 2009; http://www.eurandom.nl/events/workshops/2009/NETCOOP/).

Pierre Brémaud

- Received in 2009 the "Grand Prix France Télécom" of the French Academy of Science.
- Presentation at the "Céremonie prix de l'Académie 2009" co-organized by SMAI, INRIA and l'Académie des sciences de l'Institut de France. (IHP, Paris, November 2009; http://smai.emath.fr/spip.php?breve138&lang=fr).

Chung-Shue Chen

- Presentations at the following seminars:
  - Seminar of the Department of Networking and Networks Domain, Alcatel-Lucent Bell Labs, Villarceaux, France, June 2009,
  - INRIA Alcatel-Lucent Common Laboratory Workshop (Internal Seminar), INRIA Paris Rocquencourt, October 2009,
  - TREC's Seminar, Paris, May 2009.

Bruno Kauffmann

- Poster presentation at ACM SIGMETRICS (Seattle, USA, June 2009; http://conferences.sigmetrics.org/sigmetrics/2009),
- Talk at EuroNF Traf workshop (Paris, France, December 2009; http://perso.rd.francetelecom.fr/brown/EuroNFTraf09/),
- Participation in the Erlang Centennial Conference, organized by the Queuing System community and the Technical University of Denmark (Copenhagen, Denmark, April 2009; http://www.euro-math-soc.eu/node/152).

Marc Lelarge

- Member of the program committee of ACM SIGMETRICS 09 (Seattle, June, http://www.sigmetrics.org/conferences/sigmetrics/2009/)
- Member of the program committee of Euro-NF conference: NetCoop 2009 (Eindhoven, November http://lia.univ-avignon.fr/netcoop2008).
- Presentations at the following conferences:

    * Fifth bi-annual Conference on The Economics of the Software and Internet Industries (Toulouse, January, http://weis09.infosecon.net/).
    * IEEE INFOCOM 2009 (Rio de Janeiro, April, http://www.ieee-infocom.org/2009/).
    * ACM SIGMETRICS 2009 (Seattle, June, http://www.sigmetrics.org/conferences/sigmetrics/2009/).
    * WEIS 2009 (London, June, http://weis09.infosecon.net/).
    * Allerton 2009 (Urbana-Champaign, October, http://www.csl.illinois.edu/allerton/)
  – Participation in the following conferences:
    * IPAM Workshop: Probabilistic Techniques and Applications (Los Angeles, October, http://www.ipam.ucla.edu/programs/cmaws1).
  – Presentation at the following seminars:
    * ITA 2009 (San Diego, February, http://ita.calit2.net/workshop.php)
    * ALEA 2009 (Luminy, March, http://www.liafa.jussieu.fr/~poulalho/ALEA09/).
    * Stochastic Networks And Related Topics (Bedlewo, Poland, May, http://www.math.uni.wroc.pl/~lorek/bedlewo2009/index.php).
    * INFORMS/APS 2009 (Ithaca, July, http://appliedprob.society.informs.org/apsconf09/APS09.html).
    * Young European Queueing Theorists, EURANDOM, (Eindhoven, November, http://www.eurandom.tue.nl/events/workshops/2009/YEQTIII/index.htm).

Mir Omid Haji Mirsadeghi

  – Presentations at the Summer School of Probability, July 2009.

Frédéric Morlot

  – Presentation at the the TEMPO seminar at Orange Labs (organized by Thomas Bonald).

Van Minh Nguyen

  – Presentations at the following seminars:
    * Bell Labs France–INRIA workshop (Paris, January 2009),
    * Bell Labs France–INRIA workshop (Paris, October 2009).

Justin Salez

  – In charge of tutorials for the course “Theórie de l’Information et Codage” at ENS Paris, from January to June, 2009.
  – In charge of tutorials for the course “Graphes et Combinatoire” at Université Paris 6, from January to June, 2009.
  – In charge of the course "Formal Calculus" in *Classes Préparatoires aux Grandes, Écoles (MPSI)*, Lycée Henri IV, Paris, for the year 2009.
  – Presentation ACM-SIAM Symposium on Discrete Algorithms (SODA09) (New-York, January 2009; http://www.siam.org/meetings/da09/).
  – Participation in the following conferences:
    * Journées ALEA 2009, (CIRM, Luminy, Marsh 2009; http://www.liafa.jussieu.fr/~poulalho/ALEA09/),

  * Fifth Cornell Probability Summer School (Cornell University, Ithaca, June 2009; http://www.math.cornell.edu/~durrett/CPSS2009/).

Yogeshwaran Dhandapani

- Presentation at 39th Summer school in Probability (St. Flour, July 2009).
- Participation in the following conferences:
  * Trimester program on Statistical physics, combinatorics and probability. (IHP, Paris, September-December 2009; http://ipht.cea.fr/statcomb2009/).
- Presentation at the following seminars
  * Departement of IEOR, IIT (Powai Mumbai, India; August 2009).
  * Departement of Mathematics, Indian Institute of Science (Bangalore, India; September 2009).

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Major publications by the team in recent years

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Year Publications

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