INRIA, Evaluation of Theme Réseaux et Télécommunications

Project-team TREC

March 2012

Project-team title: TREC: Théorie des Réseaux et Communications

Scientific leader: F. Baccelli

Research center: Paris-Rocquencourt

Common project-team with: ENS Paris

1 Personnel

Personnel (November 2007)

	Misc.	INRIA	CNRS	University	**Total**
DR (1) / Professors	0.5	1			**1.5**
CR (2) / Assistant Professors		2			**2**
Permanent Engineers (3)					
Temporary Engineers (4)					
PhD Students	1.5			4	5.5
Post-Doc.					
Total	**2**	**3**		**4**	**9**
External Collaborators					
Visitors ($>$ 1 month)					

(1) “Senior Research Scientist (Directeur de Recherche)”
(2) “Junior Research Scientist (Chargé de Recherche)”
(3) “Civil servant (CNRS, INRIA, ...)”
(4) “Associated with a contract (Ingénieur Expert or Ingénieur Associé)”

Personnel (March 2012)

	Misc.	INRIA	CNRS	University	**Total**
DR / Professors		2			**2**
CR / Assistant Professor		2		1	**3**
Permanent Engineer					
Temporary Engineer					
PhD Students	3	1		3	**7**
Post-Doc.	2	1			**3**
Total	**5**	**6**		**4**	**15**
External Collaborators	1				**1**
Visitors ($>$ 1 month)					

Changes in staff

DR / Professors CR / Assistant Professors	Misc.	INRIA	CNRS	University	total
Arrival		1		1	2
Leaving	.5				.5

Current composition of the project-team (March 2012):

- Hélène Milome, administration, INRIA
- François Baccelli, DR INRIA
- Bartlomiej Błaszczyszyn, DR INRIA
- Pierre Brémaud, Scientific Adviser
- Anne Bouillard, MdC ENS
- Ana Busic, CR INRIA
- Emilie Coupechoux, Ph.D. Paris 7
- Anastasios Giovanidis, Post Doc. INRIA
- Miodrag Jovanovic, Ph.D. Cifre FT
- Paul Keeler, Post Doc. INRIA
- Gaurav Kumar, Ph.D. Paris 6
- Mathieu Leconte, Ph.D. CIFRE Technicolor
- Marc Lelarge, CR INRIA
- Mir Omid Mirsadeghi, Ph.D. INRIA–Sharif
- Frédéric Morlot, Part time Ph.D. (FT)
- Tien Viet Nguyen, Ph.D. ENS
- Chandra Singh, Post Doc. ALU
- Aurore Junier, Ph.D. IRISA-INRIA Paris, part time.

Current position of former project-team members 07-12 period:

- Hamed Amini, TREC Ph.D. AMX 07-11, now PostDoc at EPFL
- Abir Benabid, TREC Postdoc ANR 11, now Prof. in King Saud University
- Florence Bénézit, TREC Posdoc ANR–ENS 10-11, now Researcher at FT Labs
- Paola Bermolen, TREC Ph.D. 07-10, now Prof. in Montevideo University, Uruguay
- Giovanna Carofiglio, TREC Ph.D. ENST and Politecnico di Torino 06-08, now Researcher at Bell Labs
- Calvin Chen, TREC Postdoc INRIA–ALU 9-11, now Researcher at Bell Labs

- Yogeshwaran Dhandapani, TREC Ph.D. EADS 07-11, now Postdoc at Technion
- Nadir Fahri, TREC Postdoc ANR 11, now Researcher at INRETS (Institut National de Recherche sur les Transports et leur Sécurité).
- Bruno Kauffmann, TREC Ph.D. AMN 07-11, now Researcher at FT Labs
- Vivek Mhatre, TREC PostDoc Thomson 07, now Researcher at Motorola Labs
- Van Minh Nguyen, TREC Ph.D. Cifre ALU–INRIA 07-11, now with Sequans
- Justin Salez, TREC Ph.D. AMN 07-11, now Postdoc at UC Berkeley
- Minh Anh Tran, TREC Ph.D École Polytechnique 04-07, now Prof. at Paris Est University.

Last INRIA enlistments

- Ana Busic, CR2 INRIA, 09.

2 Work progress

2.1 Keywords

Short list Analysis of Algorithms; Combinatorial optimization; Information theory; Economics of networks; MAC protocols; Network calculus; Network dynamics; Network simulation; Network statistics; Point process; Queuing theory; Random graph; Routing; Stochastic geometry; Wireless network.

Extended list Ad hoc network; Admission control; Belief propagation; Boolean model; Cellular network; Cognitive radio; Congestion control; Diffusion on graphs; Error exponent; Estimator; Gossip on graphs; Insensitivity; Large deviation; Local weak convergence; MAC protocols; Markov decision; Max-plus algebra; Mesh network; Network game; Network probing; Palm calculus; Peer-to-Peer; Percolation; Perfect simulation; Power control; Product-form; Random tessellation; Shot-noise; Stochastic stability; Stochastic comparison.

2.2 Context and overall goal of the project

TREC is a joint INRIA-ENS project-team. It is focused on the mathematical 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, Sprint, Technicolor, Qualcomm and Orange. The three methodological research directions are:

1. stochastic network dynamics: stability, worst-case performance analysis using the max plus algebra, network calculus, perfect simulation, inverse problems,
2. 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
3. the analysis of random graphs: combinatorial optimization problems on graphs, analysis of graph algorithms such as belief propagation, gossip, diffusion.

The two main domains of application have been:

4 the 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;

5 economics of networks: epidemic risk model, incentives, security, insurance, diffusion of innovations, economics of geolocalization.

2.3 Objectives for the evaluation period

Here are the "plans for the next 4 years" as stated in our 2007 report:

Our first objective is still to reach **critical mass***, which we think to mean about 5 permanent researchers with the right skills and interests. If this materializes, we will try to maintain our 4 research themes for which we foresee the following evolution:*

- *The main research directions in connection with Theme 1*[1] *of our past research will be on* **overlay networks***. We will propose this as one of our research directions to the new EURO NF Network of Excellence on the Future of the Internet.*
- *The research on wireless networks (Theme 2 of our past research) will be focused on* **opportunistic and adaptive schemes***, with possible incarnations in scheduling, association, routing, power control etc. Opportunistic scheduling had a major impact on cellular networks with e.g. HSDPA. In mobile ad hoc networks, opportunistic routing strategies, which take advantage of both time and space diversity (i.e. the fluctuations due to fading and MAC), seem to significantly outperform classical routing strategies, where packets are routed on a pre-defined path usually obtained by a shortest path routing protocol and then implemented by the MAC. Fading or interference aware MAC protocols are also quite appealing in some classes of wireless LANs.*
- *We expect the research on discrete event networks (Theme 3) to be recentered on* **inverse problems** *in connection with active probing. This will be made possible thanks to the new association with D. Veitch. We may however decide to capitalize on our past achievements on stochastic discrete event networks through a monograph with S. Foss.*
- *In connection with Theme 4, we have two main evolutions in mind, both in connection with our research in communications.*
  1. *We have to go* **beyond the Poisson assumption** *for our point process and stochastic geometry models. This will require an important mathematical investment which has already started;*
  2. *We also intend to start a new research direction on* **message passing algorithms***, which builds upon our expertise on random trees/graphs and our new collaboration with D. Aldous in Berkeley. Sparse graph structures have proved useful in a number of information processing tasks (channel coding, source coding, signal processing, and recently similar design ideas have been proposed for code division multiple access communications).*

Comments

- The **critical mass** objective was reached thanks to hiring at INRIA (Ana Busic) and at ENS (Anne Bouillard).

[1]This is with respect to our 2007 report.

- The development of **overlay networking** through interactions within the EuroNF Network did not materialize. However, a promising line of research was initiated lately with the EPI GANG on Peer-to-Peer [119].

- As planned in 2007, **adaptive and opportunistic routing and MAC** schemes played a fundamental role in our basic research [2, 21, 31, 57, 56, 51, 52] as well as in our interactions with industry (Alcatel, Qualcomm and Orange) [111, 132, 44].

- Our activity on **inverse problems** in stochastic networks materialized in the thesis of B. Kauffmann [10], a series of papers with D. Veitch and J. Bolot [20, 24, 23, 36, 96, 41] and the ANR Cmon project. The project of a monograph on network dynamics with S. Foss, which was mentioned in the 2007 plans, did not materialize. However, several papers on the matter were published in collaboration with him [53, 22, 34, 43].

- The analysis of stochastic geometry models going **beyond the Poisson assumption** led to a series of important results on stochastic ordering and continuum percolation. This led to the thesis of D. Yogeshwaran [8] and a series of papers on the matter [25, 82, 42, 120, 122, 121]. Another line of thought based on factorial moment expansions was considered in [128].

- The new research direction on **message passing algorithms** was quite successful. In fact, it led to the initiation of a rich new set of research directions on random graphs and trees with two theses (J. Salez [12] and H. Amini [9]) and a series of papers on the matter, several of which with D. Aldous [61, 13, 73, 71, 33, 83, 45, 107, 97].

2.4 Objective 1 Network Dynamics

2.4.1 Personnel

François Baccelli, Abir Benabid, Florence Bénézit, Ana Bušić, Anne Bouillard, Giovanna Carofiglio, Nadir Fahri, Aurore Junier, Bruno Kauffmann

2.4.2 Project-team positioning

This traditional research topic of TREC has several classical threads such as max plus algebras, queueing theory or congestion control as well as new threads like network calculus, perfect simulation, active probing or Markov decision.

Our research on perfect sampling is conducted in collaboration with the project team MESCAL [INRIA Grenoble]; that on Markov decision processes complements the research of MAESTRO [INRIA Sophia] and LISA [University of Angers] and has a strong background on max plus algebras. The main communities in Network calculus are in the University of Pisa (Giovanni Stea), TU Kaiserslautern (Jens Schmitt).

2.4.3 Scientific achievements

Algebra 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 performance is then derived by combining these curves. Here are our main contributions:

- *Network calculus models* In envelope-based models for worst-case performance evaluation like Network Calculus or Real-Time Calculus, several types of service curves have been introduced to quantify some deterministic service guarantees. In cooperation with Éric Thierry and Laurent Jouhet [ENS Lyon], we studied in [84] and [102] the expressiveness and stability of these different definitions of service curves. The goal of these studies was to clarify the differences between the class of curves, their non-equivalence and their properties concerning computing the left-over service curves and the concatenation.

- *Deterministic performance bounds networks* In cooperation with Éric Thierry and Laurent Jouhet [ENS Lyon], we described in [85] the first algorithm which computes the maximum end-to-end delay for a given flow, as well as the maximum backlog at a server, for *any* feed-forward network under arbitrary multiplexing, with concave arrival curves and convex service curves. Its computational complexity may look expensive (possibly super-exponential), but we showed that the problem is intrinsically difficult (NP-hard). We showed that, fortunately, in some cases, like tandem networks with cross-traffic interfering along intervals of servers, the complexity becomes polynomial. In [103], we show that in tandem networks, the worst-case performance bound under arbitrary multiplexing can be obtain by a policy with static priorities, the "shortest-destination first" policy and we extend the method to static priorities. The bounds computed and no tight, but outperform the already known bounds.

- *Feed-forward networks with wormhole routing discipline and packetization* In collaboration with Bruno Gaujal [INRIA Rhône Alpes] and Nadir Farhi [GRETTIA] we are working on a model of performance bound calculus on feed-forward networks where data packets are routed under wormhole routing discipline. These results can be found in [124] and have been presented in ILAS 2011. We introduce the notion of *packet curve* that enables to take advantage of some knowledge about the length of packets in a Network calculus fashion.

- *Residuation in max plus automata* With Éric Badouel, Philippe Darondeau [INRIA/IRISA] and Jan Komenda [Institute of Mathematics, Brnó], we study in [101] the decidability of existence and the rationality of delay controllers for systems with time weights in the tropical and interval semirings. Depending on the max plus or min plus rationality of the series specifying the controlled system and the control objective, cases are identified where the controller series defined by residuation is rational, and when it is positive (i.e., when delay control is feasible). When the control objective is specified by a tolerance, i.e. by two bounding rational series, a nice case is identified in which the controller series is of the same rational type as the system specification series.

Statistics 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 statistical methodologies. Here are our main contributions to this field:

- **Inverse Problems** In [23], we formulated 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. [23] provides a general definition of the inverse problems in this class and maps out the key variants: the analytical methods, the statistical methods and the design of experiments. We also showed how this inverse problem viewpoint translates to the design of concrete Internet probing applications.

In his thesis [10], B. Kaufmann also investigated inverse problems in bandwidth sharing networks theory. A bandwidth sharing networks allocates the bandwidth to each flow in order to maximize a given utility function (typically an α-fairness), with the constraints given by the capacity of the different servers.

- **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 combined classical queueing theory models with statistical analysis to obtain estimators of residual bandwidth on all links of the path. These estimators were proved to be tractable, consistent and efficient. In [24] we evaluated their performance with simulation and trace-based experiments.

  This method has been generalized in [36] to a probing multicast tree instead of a single path.

Simulation 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.

- **Reducing the number of trajectories** In collaboration with Bruno Gaujal [INRIA Grenoble - Rhône-Alpes], we proposed in [126] 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. The envelope technique has been implemented in a software tool PSI2.

  When the cardinality of the state space makes challenging even storing the state of the Markov chain, we proposed to combine the ideas of bounding processes and the aggregation of Markov chains [104]. We illustrated the proposed approach of aggregated envelope bounding chains on queueing models with joint arrivals and joint services, often referred to in the literature as assemble-to-order systems.

- **Speeding up the simulation** In collaboration with Bruno Gaujal [INRIA Grenoble - Rhône-Alpes], we also proposed a new method to speed up perfect sampling of Markov chains by skipping passive events during the simulation [112]. We showed that this can be done without altering the distribution of the samples.

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).

- **Numerical Solutions and Bounds** In collaboration with Jean-Michel Fourneau [PRiSM, Université de Versailles Saint-Quentin] we proposed an iterative algorithm to compute component-wise bounds of the steady-state distribution of an irreducible and aperiodic Markov chain [88, 87]. These bounds are based on very simple properties of max plus and min plus sequences. We showed that, under some assumptions on the Markov chain, these bounds converge to the exact solution. Furthermore, at every step we know that the exact solution is within an interval, which provides a more effective convergence test than usual iterative methods [46].

  In a joint work with I.M. H. Vliegen [University of Twente, The Netherlands] and A. Scheller-Wolf [Carnegie Mellon University, USA] [130], 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.

- **Model decomposition** In collaboration with Jean-Michel Fourneau [PRiSM, Université de Versailles Saint-Quentin] 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. We show how stochastic monotonicity can be used to answer these questions [49].

- **Censored Markov Chains** (CMC) allow one to represent the conditional behavior of a system within a subset of observed states. Unfortunately, the stochastic matrix of a CMC may be difficult to obtain. Dayar et al. (2006) have proposed an algorithm, called DPY, that computes a stochastic bounding matrix for a CMC with a smaller complexity with only a partial knowledge of the chain. In [86], we proved that this algorithm is optimal for the information they take into account.

- **Critical Level Policies in Controlled Queuing Systems** In a joint work with Emmanuel Hyon [University of Paris Ouest Nanterre La Defense and LIP6] [113], we consider a single-item lost sales inventory model with different classes of customers. Each customer class may have different lost sale penalty costs. We assume that the demands follow a Poisson process and we consider a single replenishment hypoexponential server. We give a Markov decision process associated with this optimal control problem and prove some structural properties of its dynamic programming operator. This allows us to show that the optimal policy is a critical level policy. We also discuss some possible extensions to other replenishment distributions.

Stochastic Stability

- **Ergodicity of Probabilistic Cellular Automata** In a joint work with J. Mairesse and I. Marcovici [LIAFA, CNRS and Université Paris 7] [105], we considered ergodicity properties of probabilistic cellular automata (PCA). A classical cellular automaton (CA) is a particular case of PCA. For a 1-dimensional CA, we proved that ergodicity is equivalent to nilpotency, and is therefore undecidable. We then proposed an efficient perfect sampling algorithm for the invariant measure of an ergodic PCA. Our algorithm does not assume any monotonicity properties of the local rule. It is based on a bounding process which is shown to be also a

PCA. We then focused on the PCA Majority, whose asymptotic behavior is unknown, and performed numerical experiments using the perfect sampling procedure.

- **Ergodicity of Spatial Queues** In a joint work with S. Foss [Heriot–Watt University, UK] [43], we considered 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.

- **Ergodicity of the Bipartite Matching Queueing Model** In a joint work with V. Gupta [Carnegie Mellon University, USA] and J. Mairesse [LIAFA, CNRS and Université Paris 7] [117], we considered the bipartite matching queueing model of customers and servers introduced by Caldentey, Kaplan, and Weiss (Adv. Appl. Probab., 2009). Customers and servers play symmetrical roles. There is a finite set C, resp. S, of customer, resp. server, classes. Time is discrete and at each time step, one customer and one server arrive in the system according to a joint probability measure μ on $C \times S$, independently of the past. Also, at each time step, pairs of *matched* customer and server, if they exist, depart from the system. Authorized *matchings* are given by a fixed bipartite graph $(C, S, E \subset C \times S)$. A *matching policy* is chosen, which decides how to match when there are several possibilities. Customers/servers that cannot be matched are stored in a buffer.

  The evolution of the model can be described by a discrete time Markov chain. We studied its stability under various admissible matching policies including: ML (Match the Longest), MS (Match the Shortest), FIFO (match the oldest), priorities. There exist natural necessary conditions for stability (independent of the matching policy) defining the maximal possible stability region. For some bipartite graphs, we prove that the stability region is indeed maximal for any admissible matching policy. For the ML policy, we proved that the stability region is maximal for any bipartite graph. For the MS and priority policies, we exhibited a bipartite graph with a non-maximal stability region.

Congestion Control Most of our work has been on improvements of TCP:

- **Split TC** 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 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.

- **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 [65] 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.

2.4.4 Collaborations

- Thalès, Real-Time-at-Work and ONERA on embedded networks.
- Grenouille on probing in access networks http://www.grenouille.com/.
- D. Mc Donald [University of Ottawa] and S. Foss [Heriot–Watt] on congestion control [14, 53, 22].
- S. Foss [Heriot–Watt] [43] and J. Mairesse [LIAFA, Paris 7] [105] on stochastic stability
- J.M. Fourneau [Université de Versailles] on numerical methods [88, 87]
- Bruno Gaujal [INRIA Rhône Alpes] on network calculus [124] and on perfect sampling [126]
- Éric Thierry and Laurent Jouhet [ENS Lyon] on network calculus [84, 85, 102].

2.4.5 External support

- *ANR PEGASE* http://sites.onera.fr/pegase/ financing Post-docs on network calculus
- *ANR CMON* http://wiki.grenouille.com/index.php/CMON financing post-doc in 2010 on Network Tomography.

2.4.6 Self assessment

Strong Points On most of the new topics listed above, a community has been shaped up in France and in Europe: for instance, the WEED (Worst-End-to-End Delays) group has been founded and a workshop has been organized; a workshop on Structural Properties in Markov Decision Processes has also been organized within the ARC OCOQS.

Evolution Some traditional themes of TREC (like congestion control) have almost vanished. This is compensated by the new themes that developed thanks to the recent arrivals in the team. We explain in the Future Plans section how to better connect the new activities in network dynamics with those on spatial networks.

2.5 Objective 2: Point Processes, Stochastic Geometry and Random Geometric Graphs

2.5.1 Personnel

François Baccelli, Bartłomiej Błaszczyszyn, Pierre Brémaud, Yogeshwaran Dhandapani, Kumar Gaurav, Mir Omid Haji Mirsadeghi, Tien-Viet Nguyen

2.5.2 Project-team positioning

This research domain is centered on the development of tools and methodology for the spatial analysis of communication network models.

TREC is known for its contributions to point process theory[2]. In the last years, we are also recognized in the mathematical community working on stochastic geometry. Stochastic geometry is a rich branch of applied probability which allows to study random phenomenons on the plane or in higher dimension. This community is centered around the biannual workshop SGSIA (cf. http://csgb.dk/events/2011/sgsia11/). B. Blaszczyszyn was appointed chair of the next edition of this conference to be held in 2013 in Toruń (Poland). At the national level, TREC has participated in the mounting of the Research Group (Groupement de recherche, GdR) on Stochastic Geometry led by Pierre Calka (Université de Rouen); http://gdr-geostoch.math.cnrs.fr/ This GdR is going to be a collaboration framework for all French research teams working in the domain of spatial stochastic modeling, both on theory development and in applications.

2.5.3 Scientific achievements

Monograph on Stochastic Geometry and Wireless Networks In 2008–2009 we finished and published our two volume book project [1, 2] focused on the use of the stochastic geometry framework for the modeling of wireless communications. Our book offers a structured survey of results obtained by this approach in 2000–2009 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 relevan 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.

Beyond the Poisson Assumption in Network Modeling Stochastic models of wireless networks are usually investigated under deterministic lattice (usually hexagonal) or Poissonian setting. Both assumptions are too simplistic. In reality, patterns of base stations are neither perfectly periodic, due to various locational constants nor completely independent because of various interactions: social, human interactions typically introduce more clustering, while the medium access protocols implemented in mobile wireless devices (as e.g. CSMA used in the popular WiFi technology) tend to separate active users. Our results in this domain lay the groundwork for more adequate stochastic models.

- *Research on Comparison of Spatial Homogeneity of Random Measures and Point Processes* In the PhD thesis [8] of D. Yogeshwaran, we were looking for stochastic orders allowing to compare point processes having the same mean measures and differing by how strongly they cluster their points. One of them, proposed in [122], is based on the joint examination of void probabilities and factorial moment measures. We prove that *determinantal*

[2]P. Brémaud Point Processes and Queues: Martingale Dynamics, Springer-Verlag, 2005; F. Baccelli and P. Brémaud, Elements of Queueing Theory, Springer-Verlag, 2003.

and *permanental* processes, as well as, more generally, *negatively* and *positively associated* point processes are comparable in this sense to the Poisson point process of the same mean measure. A stronger comparison, proposed in [25] and called dcx, allows to compare expected values of all dcx function (having all second order derivatives non-negative) of point processes. We show that non-negative integral shot-noise fields with respect to dcx ordered random measures inherit this ordering from the measures. This observation allows, in particular, to compare the impact of the structure of pattern of interfering points on the performance of a wireless channel whenever the QoS metric is convex or concave with respect to the interferences (as e.g. the Shannon's $\log(1+\mathrm{SINR})$ law or the outage probability in Rayleigh channel). For dcx ordering, in [122], we provide a large monotone spectrum of comparable point processes, called *perturbed lattices*, ranging from periodic grids to Cox processes, and encompassing Poisson point process as well. They are intended to serve as a platform for further theoretical and numerical studies of clustering in networking.

- *Spatial Homogeneity and Percolation* Percolation in Boolean model (called also Random Geometric Graph) was proposed in a pioneering work "Random plane networks" by E. Gilbert (1961) as a macroscopic models for connectivity in large wireless networks. Heuristics indicate that clustering (opposite of spatial homogeneity) of a point process negatively impacts the percolation. In [8, 82, 121] we studied this heuristic using our stochastic comparison tools. We show, in particular, that all processes "more regular" than Poisson point process exhibit non-trivial phase transition in their Boolean percolation models. We also extended these results to the SINR percolation model.

- *Spatial Homogeneity and Fist Passage Percolation* In [42] we studied optimal navigations in wireless networks in terms of first passage percolation on some space-time SINR graph. Existence of arbitrarily large voids in Poisson pp was shown to be a reason of infinite end-to-end packet-delivery delays in a time-space SINR model. Superposing the Poisson pp with an independent lattice of arbitrarily small intensity makes the delays finite. The latter result remains true when using a simple perturbed lattice, in which case the superposition is an example of a (dcx) sub-Poisson pp.

Stochastic Geometry and Information Theory It should be obvious now that stochastic geometry is useful in modeling of network topology. In [116], a joint work with V. Anantharam [UC Berkeley], we proved that it can be also used to obtain results of information theoretic nature, namely to the estimation of error exponents in Shannon's additive noise channel with power constraints on the codewords. The following channel is considered: One observes the whole realization of some initial stationary (mother) point process in n-dimensional Euclidean space, and one (daughter) point from the image of the mother process obtained by independent displacement of all points by noise vectors of a given law. The decoding problem consists in finding the inverse image (the mother point) of that daughter point in the initial pattern. The Shannon regime is that where the dimension n tends to infinity and where the logarithm of the intensity of the point process is proportional to n. We showed that this problem exhibits 0-1 phase transition for the probability of right estimation depending on whether the sum of the proportionality factor and of the differential entropy rate of the noise is positive or negative. We also use large deviations theory to find explicit bounds on error exponents for two classes of mother point processes: Poisson and Matérn.

Hawkes Point Processes In collaboration with S. Foss [Heriot-Watt University], P. Brémaud has proved the ergodicity of a new point process model combining the classical stress release model with the Hawkes model [34]. This combines tools from point process theory, in particular stochastic intensity, with tools from general state space Markov chains (Harris chain theory, Foster criterion for ergodicity).

2.5.4 Collaborations

- UC Berkeley, USA (V. Anantharam) on information theory and point processes in high dimensional spaces [50, 116].
- VTT (Ilkka Norros) and INRIA GANG (Fabien Mathieu) [119] on point processes in peer-to-peer.
- Heriot-Watt University (Serguei Foss) on point processes and stochastic geometry [34, 43].

2.5.5 External support

- *Scientific partnership with EADS* financed the PhD student D. Yogeshwaran.
- *Associate team IT-SG-WN* from 2011; `http://www.inria.fr/en/teams/it-sg-wn` on Information-Theoretic Capacity and Error Exponents of Stationary Point Processes under Random Additive Displacements.
- *EIT ICT Labs Project FUN* in 2011 on spatial birth and death processes.

2.5.6 Self assessment

We are recognized in the international stochastic-geometric community. This community is not yet well structured in France. We are really glad that this year the application for the GdR on Stochastic Geometry has been accepted by the National Committee of CNRS and the group will be officially created in 2012.

2.6 Objective 3: Random Graphs and Combinatorial Optimization

2.6.1 Personnel

Hamed Amini, Ana Bušić, Emilie Coupechoux, Mathieu Leconte, Marc Lelarge, Justin Salez.

2.6.2 Project-team positioning

- within INRIA: Algorithms, discrete mathematics and combinatorial optimization are some the research fields of MASCOTTE. Our focus is quite different as we concentrate on probabilistic methods. We are also participating actively to the working group ALEA concentrating on combinatorics and analysis of algorithms.
- International: there are may researchers working on random graphs. Our focus is at the intersection of this topic and computer science. We are in contact with David Gamarnik, Devavrat Shah (MIT) or Andrea Montanari (Stanford) who have a similar focus.

2.6.3 Scientific achievements

Combinatorial optimization and its scaling exponents

A very simple example of an algorithmic problem solvable by dynamic programming is to maximize, over sets A in $\{1, 2, ..., n\}$, the objective function $|A| - \sum_i \xi_i 1(i \in A, i+1 \in A)$ 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 [18], with David Aldous and Charles Bordenave, we show 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.

In [13], with David Aldous and Charles Bordenave, we study the relation between the minimal spanning tree (MST) on many random points and the 'near-minimal' tree which is optimal subject to the constraint that a proportion δ of its edges must be different from those of the MST. Heuristics suggest that, regardless of details of the probability model, the ratio of lengths should scale as $1 + \theta(\delta^2)$. We prove this scaling result in the model of the lattice with random edge-lengths and in the Euclidean model.

Belief Propagation for the Random Assignment Problem

Belief propagation is a non-rigorous decentralized and iterative algorithmic strategy for solving complex optimization problems on large 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 phenomena (general conditions for convergence, asymptotic speed and influence of the initialization) still misses. The objective method consists in using the notion of local weak convergence of random geometric graphs to define a limiting local structure as the number of vertices grows to infinity and then replace the asymptotic study of the phenomenon by its direct analysis on the infinite graph.

This method 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. It has been published in [28] and appeared in [73]. 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.

Resolvent and Rank of Large Random Graphs

In [33], with Charles Bordenave, we analyze the convergence of the spectrum of large random graphs to the spectrum of a limit infinite graph. We apply these results to graphs converging locally to trees and derive a new formula for the Stieljes transform of the spectral measure of such graphs. We illustrate our results on the uniform regular graphs, Erdős-Rényi graphs and preferential attachment graphs. We also give examples of application for weighted graphs, bipartite graphs and the uniform spanning tree of n vertices.

In [83], [45], with Charles Bordenave, we investigate the rank of the adjacency matrix of large diluted random graphs: for a sequence of graphs converging locally to a Galton-Watson tree, we provide an explicit formula for the asymptotic multiplicity of the eigenvalue 0 in terms of the degree generating function. In the first part, we show that the adjacency operator associated with a Galton-Watson tree is self-adjoint with probability one ; we analyze the associated spectral measure at the root and characterize the distribution of its atomic mass at 0. In the second part, we established a sufficient condition for the expectation of this atomic mass to be precisely the normalized limit of the dimension of the kernel of the adjacency matrices of the sequence of graphs. Our proofs borrow ideas from analysis of algorithms, functional analysis, random matrix theory, and statistical physics.

Matchings in infinite graphs and Counting spanning subgraphs subject to local constraints

In [123], we prove 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 consider 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 allows 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 show 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 are 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.

In [129], we use negative association and local weak convergence to establish the validity of the cavity method for counting spanning subgraphs subject to local constraints. Specifically, the normalized logarithm of the associated generating polynomial (or partition function) is shown to converge along any sequence of graphs whose random weak limit is a tree, and the limit is directly expressed in terms of the unique solution to a limiting cavity equation. On a Galton-Watson tree, the latter simplifies into a recursive distributional equation which can be solved explicitly. As an illustration, we provide an asymptotic formula for the maximal size of a spanning subgraph with maximal degree b in the Erdős-Rényi model with fixed average degree and diverging size, for any b.

Bipartite graph structures for efficient balancing of heterogeneous loads

With Laurent Massoulié, 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 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 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.

Analysis of Diffusions: Efficient Control of Epidemics, Bootstrap Percolation and Flooding in Weighted Random Graphs

Using the same model as in [118], we quantify in [71], 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.

The bootstrap percolation model has been used in several related applications. In [29] , we consider bootstrap percolation in living neural networks extending the work of [118]. 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 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.

In a joint work [97] with Moez Draief, we study 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 analyze 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 show that these quantities grow as the logarithm of n, when the size of the graph n tends to infinity. We also derive the exact value for the prefactors.

This result allows 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.

Density Classification on Infinite Lattices and Trees

In a joint work with Fatès [INRIA Nancy – Grand-Est], J. Mairesse and I. Marcovici [LIAFA, CNRS and Université Paris 7] [125] 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.

2.6.4 Collaborations

- David Aldous [UC Berkeley]: [18], [13]
- Charles Bordenave [CNRS and Université de Toulouse]: [18], [13], [33], [83], [45], [123]
- Moez Draief [Imperial College London]: [97]
- Laurent Massoulié [Technicolor]: co-advising of Mathieu Leconte
- Devavrat Shah [MIT]: [28], [73].

2.6.5 External support

PhD grant of Mathieu Leconte funded by Technicolor.

2.6.6 Self assessment

- Weak points: there are very few groups working on these techniques in France. The community being very small, training students requires a lot of energy and students with a PhD at the interface of mathematics and computer science are sometimes not appreciated correctly.

- Strong points: this field of research is well-suited for our ENS students. We started this line of research and were able to attract already very good students and obtained publications in the main probability and computer science journals as example: Annals of Probability or SIAM Journal on Computing.

2.7 Objective 4: Modeling and performance analysis of wireless networks

2.7.1 Personnel

François Baccelli, Bartłomiej Błaszczyszyn, Miodrag Jovanovic, Bruno Kauffmann, Mir Omid Haji Mirsadeghi, Frédéric Morlot, Tien Viet Nguyen, Van Minh Nguyen,

2.7.2 Project-team positioning

TREC played a pioneering role in using stochastic geometry for the modeling of wireless networks. This domain of research is now expanding very fast. The publication of the book [1, 2], presentations at conferences and collaborating with many leading researchers in this domain, all led to the high visibility of this research line.

Our main collaboration partners in Inria are the project-teams HIPERCOM, MAESTRO and recently GANG. Regarding international collaborations we have strong relations with the University of California Berkeley (D. Tse, V. Anantharam), Stanford University (Abbas El Gamal, N. Bambos), UT Austin (J. Andrews, G. de Veciana, S. Shakkottai), IIT Madras (R. Ganti) We have also a few strong industrial (telecom) partners (ALU, Qualcomm, Sprint, Orange).

Our recent research was focused on *opportunistic and adaptive schemes*, with possible incarnations in scheduling, association, routing, power control etc. We were motivated by *information theoretic* limitations of wireless communications. We started developing tools for time-space dynamics analysis. This gave us handle to address this challenging class of problems in collaboration with our partners in this field.

2.7.3 Scientific achievements

Below we structure our contributions in terms of network classes.

Cellular/Access 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, Orange Labs and Sprint. Our main scientific achievements in this domain include the following results.

- *Self-Optimization of Radio Resources in Cellular Access Networks* In [39], in collaboration with N. Bambos, [Stanford] and N. Gast [EPFL], we formulated a distributed, scalable, delay-power control (DPC) scheme for wireless networking, which balances delay against transmitter power on each wireless link. It is shown that DPC converges to a unique equilibrium power. Several key properties are established, concerning the nature of channel bandwidth sharing achieved by the links, showing some advantages with respect to the well-known Foschini-Miljanic (FM) scheme for transmitter power control in wireless networks. Based on the DPC and FM schemes, two protocols are developed, which leverage adaptive tuning of DPC parameters. One of them is inspired by TCP and exhibits analogous behavior.

  In [47], in collaboration with Alcatel–Lucent, we studied the weighted sum rate maximization problem in wireless networks consisting of multiple source-destination pairs, by adjusting the power of each user. The problem is in general a non-convex optimization problem that will lead to multiple local maxima. A Gauss-Seidel type iterative power control algorithm was presented and studied in this context.

In [90], we developed mathematical and algorithmic tools based on Gibbs' sampler 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 were proposed. We focused on the optimization of transmit power and of user association.

The global utility minimized is linked to potential delay fairness. The distributed algorithm adaptively updates the system parameters and achieves global optimality by measuring SINR and interference. The approach has been extended to heterogeneous networks in [106], and multiple antenna transmitters in [109] showing that the proposed scheme can outperform today's default modes of operation in network throughput, energy efficiency, and user fairness. Three patents were filed under the INRIA/Alcatel–Lucent joint laboratory.

- *Shadowing as Stochastic Resonance in Cellular Networks with Opportunistic Handover* Shadowing is believed to degrade the quality of service (QoS) in wireless cellular networks. In [79], in collaboration with M.K. Karray [Orange Labs], we discovered a more subtle reality. We observe, as commonly expected, that a strong variance of the log-normal shadowing increases the mean path-loss with respect to the serving BS, which in consequence, may compromise QoS. However, in some cases, an increase of the variance of the shadowing can significantly reduce the mean interference factor and, in consequence, improve some QoS metrics in interference limited systems, provided the opportunistic handover policy selects the strongest BS as the serving one. We exemplify this phenomenon, similar to stochastic resonance, 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. This work got the best-paper award of WMNC in 2010.

- *Opportunistic Scheduling in OFDMA Cellular Networks* In [44, 67], in collaboration with M.K. Karray [Orange Labs] we analyze mean long-term user throughput achieved by opportunistic (with respect to fading) scheduling policies. The developed explicit formulas tell us that the gain induced by the opportunism can fully compensate the channel degradation caused by the fading, which is of order of 13% when compared to Additive White Gaussian Noise (AWGN) channel. This work got the best-paper award of ComNet in 2009.

- *Best Signal Quality in Wireless Network* In his PhD thesis [11], see also [35, 94], Van Minh Nguyen developed a framework for analyzing the joint distribution of the best signal and interference power, using shot noise models for the interference field. The characterization of this distribution is of primary importance for the evaluation of the performance of opportunistic schemes in cellular networks.

- *Cellular Network Tomography* The well known algorithm proposed by Foschini and Miljanic in 1993 and used for power control in cellular networks allow for an optimal choice of powers by the users in a distributed, way when such a solution exists for a given configuration of requested bit rates. We have been working on the estimation of the feasible user bit rates from local measurements. We showed that by simply changing their SINR target slightly and by listening to the evolution of interference, users can locally inverse Foschini-Miljanic's algorithm and compute their residual bandwidth.

- *Coverage in Heterogeneous Cellular Networks* In a joint work with J. Andrews and R. Ganti [UT Austin, USA] [38, 108], we developed general models based on homogeneous Poisson point processes for heterogeneous networks (as composed of macro pico and femto cells) allowing for explicit analysis pf signal-to-noise-plus-interference ratio (SINR) coverage probabilities and rates. In addition to being more tractable than the usual grid models, the proposed model may better capture the increasingly opportunistic and dense placement of base stations in urban cellular networks with highly variable coverage radii.

- *Simultaneous Decoding* In [40], in collaboration with A. El Gamal [Stanford, USA] and D. Tse [UC Berkeley, USA], we analyzed a network made of a collection of transmitter-receiver links where each link is considered to be part of a Multiple Access Channel (MAC) together with a collection of co-transmitters. The necessary and sufficient condition for the feasibility of some rate when using successive interference cancellation and simultaneous decoding were provided. The gain obtained when using this type of simultaneous decoding rather than treating interference as noise was then quantified in a network made of a large random collection of such links. The gain in coverage and rate were analyzed in terms of ensemble averages, evaluated using stochastic geometry. The whole analysis was conducted in the AWGN case.

- *Self-Optimization of Neighbor Cell List* In [95], in collaboration with Alcatel–Lucent, we developed an automatic method for the optimization of the list of neighboring cells. This has an important impact on the number of dropped calls and is traditionally optimized manually with the help of planning tools.

MANETs, VANETs and Sensor Networks We focus medium access (MAC) and routing layer in Mobile Ad Hoc Networks (MANETs) which are 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. Vehicular Ad Hoc NETworks (VANETs), special cases of such networks, where network is formed between vehicles, are today the most promising civilian application for MANETs. We collaborate on these subjects with Paul Mühlethaler [INRIA HIPERCOM], E. Altman [INRIA MAESTRO], T. Richardson [Qualcomm] and G. de Veciana [UT Austin].

Our main scientific achievements in this domain include the following results.

- *Improving CSMA* This is the most popular medium access mechanism ad hoc networks, in which a node verifies the absence of other traffic before transmitting and, in the version CSMA/CA with RTS/CTS, tries to establish guard zones for its transmission.

  In [100], using tools from stochastic geometry, in collaboration with Qualcomm, we considered the problem of simultaneous scheduling of the maximum number of links that can achieve a given SINR. We showed that a simple modification to the RTS/CTS mechanism, consisting in using SINR to define the transmission guard zones, improves the performance of CSMA. Moreover, combining this with a simple modification to the transmit power level, namely 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.

  In [110], in collaboration with G. de Veciana [UT Austin, ECE] we studied the benefits of channel-aware (opportunistic) scheduling of transmissions in CSMA/CA. The key challenge in optimizing the performance of such systems is finding a good compromise among three interdependent quantities: the density of nodes, the channel quality of the scheduled transmitters, and the resulting interference at receivers. We propose two new channel-aware slotted CSMA protocols: opportunistic CSMA (O-CSMA) and quantile-based CSMA (QT-CSMA) and develop stochastic geometric models allowing us to quantify their performance in terms of spatial reuse and spatial fairness. When properly optimized these protocols offer substantial improvements in terms of both of these metrics relative to CSMA - particularly when the density of nodes is moderate to high. Moreover, we show that a simple version of QT-CSMA can achieve robust performance gains without requiring careful parameter optimization.

- *Understanding and Improving Aloha* 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 as shown in a our paper "An Aloha protocol for multihop mobile wireless networks" IEEE Trans. Inf. Theory 52 (2006). Building on the success of this highly cited paper (more than 270 times according to Google Scholar) we continue studding Aloha in collaboration with P. Mühlethaler [INRIA HIPERCOM].

  In [80] we extended the model to *non-slotted Aloha*. Comparing the performance of the two (slotted vs non-slotted) models, we observed 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.

  In [21] we analyzed 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 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.

  In [75] we analyzed the *local delays* caused by Aloha, 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 choice of the receiver (at the routing layer) 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. We showed 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 (observed before in different context), which in turn explains why we have infinite spatial average. Adaptive coding offers another nice way of breaking the outage/RESTART logic. We showed examples where the average delays are finite in the adaptive coding case, whereas they are infinite in the outage case.

- *MAC mechanisms with Performance Guarantees* By this, we mean mechanisms where each accepted connection obtains a minimum rate or equivalently a minimum SINR level — which is not guaranteed by CSMA/CA. Two such MAC algorithms were defined and compared in the PhD thesis of P. Bermolen [7] (see also [78]) jointly supervised with Télécom ParisTech. Both take the interference level into account to decide on the set of connections which can access the shared channel at any given time. A thorough comparison of the performance of these two mechanisms and CSMA/CA was performed, based on a mix of analytical models and simulation and on a comprehensive set of performance metrics which include spatial reuse and power efficiency, allowing to identify which of the proposed mechanisms outperforms CSMA/CA best depending on the scenario.

- *Opportunistic Routing in MANETs* In [31], we studied an opportunistic routing, when 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. Firstly we showed that it is possible to implement such opportunistic routing using some relay self-selection technique called "active signaling" similar to this proposed in the Hiperlan 2 standard. Moreover, it 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. Our solution works well provided only a small number of nodes in the network know their geographical positions exactly.

- *VANETS* In a series of papers [68, 69, 56] we revisited our 2D MANET models to adapt them to 1D scenario of VANETS.

- *Sensor networks* In [58] we considered a hybrid wireless sensor network with regular and transmit-only sensors. The transmit-only sensors do not have the receiver circuit, hence are cheaper and less energy consuming, but their transmissions cannot be coordinated. Regular sensors, also called cluster-heads, are responsible for receiving information from the transmit-only sensors and forwarding it to sinks. We defined and evaluated packet admission policies at cluster heads for different performance criteria. We showed that the proposed hybrid network architecture, using the optimal policies, can achieve substantial dollar cost and power consumption savings as compared to conventional architectures while providing the same performance guarantees.

Cognitive Radio In [92, 93] we proposed a probabilistic model based on stochastic geometry to analyze cognitive radio in a mobile ad hoc network using carrier sensing multiple access. Analytical results were 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.

In [81] we assumed Aloha for both primary and secondary radio networks, and using analytical models we showed the two radio networks can coexist within the same area adapting their transmission parameters simultaneously to achieve the following goal: the primary network maintains its performance with a maximum and fixed degradation whereas the secondary network maximizes its transmission throughput.

2.7.4 Collaborations

- Alcatel-Lucent Bell Laboratories (L. Thomas and L. Roulet) on self optimization in cellular networks [35, 95, 111, 109].

- Qualcomm (T. Richardson and his group) on improvements of CSMA CA [100, 132].

- Orange Labs (M. Karray) on cellular networks [55, 56, 54, 66, 67, 79, 44].

- Sprint (J. Bolot anf H. Zang) on user localization [96].

- Stanford, USA (A. El Gamal) on information theory [98, 40] and (N. Bambos) on self-optimization of radio resources [39].
- UC Berkeley, USA (D. Tse, V. Anantharam) on information theory [50, 116, 98, 40].
- INRIA HIPERCOM (Paul Mühlethaler) MAC and routing in MANETs, VANETs. [57, 56, 81, 75, 68, 69].

2.7.5 External support

- *ANR CMON* http://wiki.grenouille.com/index.php/CMON financing post-doc in 2010 on Cellular Network Tomography.
- *NoE Euro-NF* http://euronf.enst.fr/en_accueil.html; (2008–2012) Self-optimization in wireless cellular networks and sensor networks,
- *Associate team IT-SG-WN* from 2011; http://www.inria.fr/en/teams/it-sg-wn on simultaneous decoding in cellular networks.
- *CRE with Orange Labs* in 2010 on the impact of the shadowing on the quality of service in cellular networks.

2.7.6 Self assessment

Strong Points We think we more than fulfilled our objectives of 2007 in this axis. Our strong points are academic collaborations with leading theoreticians in this domain, the shaping of a community using our tools (in Europe and in the USA, but also in Asia) and the impact of our work on industry that led to several industrial point-to-point collaborations.

Weaknesses We did not manage to obtain a more stable financial support for this axis, despite several repeated attempts at major European and French research agencies. We think that this is due to the fact that, in the field of communications, decisions in these agencies are dominated by industrial research representatives, which do not want to support more fundamental and hence more challenging projects.

2.8 Objective 5: Economics of Networks

2.8.1 Personnel

François Baccelli, Emilie Coupechoux, Marc Lelarge

2.8.2 Project-team positioning

- within INRIA: tools from game theory have been developed in MAESTRO (Eitan Altman...) or DYONISOS (Bruno Tuffin...) for the analysis of resource sharing in communication networks. Our focus concerning the economics of networks is different and is not related to resource sharing.
- International: Jean Walrand and Venkat Anantharam (UC Berkeley) have recent work related to our analysis of economics of information security. We are also in contact with Sanjeev Goyal (Cambridge) and Fernando Vega-Redondo (European University Institute, Florence), who are economists working on social networks.

2.8.3 Scientific achievements

Analysis of Security Investments in Networks

Getting new security features and protocols to be widely adopted and deployed in the Internet has been a continuing challenge. There are several reasons for this, in particular economic reasons arising from the presence of network externalities. Indeed, like the Internet itself, the technologies to secure it exhibit network effects: their value to individual users changes as other users decide to adopt them or not. In particular, the benefits felt by early adopters of security solutions might fall significantly below the cost of adoption, making it difficult for those solutions to gain attraction and get deployed at a large scale.

With Jean Bolot, our goal in [63] and [62] is to model and quantify the impact of such externalities on the adoptability and deployment of security features and protocols in the Internet. We study a network of interconnected agents, which are subject to epidemic risks such as those caused by propagating viruses and worms, and which can decide whether or not to invest some amount to deploy security solutions. The risks faced by an agent depend not only on the choices of that agent (whether or not to invest in self-protection), but also on those of the other agents. Hence, expectations about choices made by other agents then influence investments in self-protection, resulting in a possibly suboptimal outcome overall.

We presente and solve an analytical model where the agents are connected according to a variety of network topologies. Borrowing ideas and techniques used in statistical physics, we derive analytical solutions for sparse random graphs, for which we obtained asymptotic results. We show that we can explicitly identify the impact of network externalities on the adoptability and deployment of security features. In other words, we identify both the economic and network properties that determine the adoption of security technologies. Therefore, we expect our results to provide useful guidance for the design of new economic mechanisms and for the development of network protocols likely to be deployed at a large scale.

In [70], we extend our study. 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.

Cyber Insurance as an Incentive for Internet Security

Managing security risks in the Internet has so far mostly involved methods to reduce the risks and the severity of the damages. Those methods (such as firewalls, intrusion detection and prevention, etc) reduce but do not eliminate risk, and the question remains on how to handle the residual risk. In [60] and [59], we consider the problem of whether buying insurance to protect the Internet and its users from security risks makes sense, and if so, of identifying specific benefits of insurance and designing appropriate insurance policies.

Using insurance in the Internet raises several questions because entities in the Internet face correlated risks, which means that insurance claims will likely be correlated, making those entities less attractive to insurance companies. Furthermore, risks are interdependent, meaning that the decision by an entity to invest in security and self-protect affects the risk faced by others. 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.

Our first key result with Jean Bolot in [60], [59] is that using insurance would increase the security in the Internet. Specifically, we show that the adoption of security investments follows a threshold or tipping point dynamics, and that insurance is a powerful incentive mechanism which pushes entities over the threshold into a desirable state where they invest in self-protection. Given its many benefits, we argued that insurance should become an important component of risk management in the Internet, and discussed its impact on Internet mechanisms and architecture.

In a subsequent work with Jean Bolot [72], 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.

Diffusion and Cascading Behavior in Random Networks

Viral marketing takes advantage of preexisting social networks among customers to achieve large changes in behaviour. Models of influence spread have been studied in a number of domains, including the effect of 'word of mouth' in the promotion of new products or the diffusion of technologies. A social network can be represented by a graph where the nodes are individuals and the edges indicate a form of social relationship. The flow of influence through this network can be thought of as an increasing process of active nodes: as individuals become aware of new technologies, they have the potential to pass them on to their neighbours. The goal of marketing is to trigger a large cascade of adoptions. In [64], with Moez Draief, we develop a mathematical model that allows to analyze the dynamics of the cascading sequence of nodes switching to the new technology. To this end we describe a continuous-time and a discrete-time models and analyse the proportion of nodes that adopt the new technology over time.

The spread of new ideas, behaviors or technologies has been extensively studied using epidemic models. In [61], [118], 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.

In [107] we extend previous results to a model of random graphs having both a given degree distribution and a tunable clustering coefficient. This work shed new light on the impact of clustering on the spread of new ideas, technologies, viruses or worms. We consider two types of growth processes: the (classical SI) diffusion model, and the contagion model, which is inspired by a simple coordination game played on the network and is characterized by a threshold rule and a random seed. While clustering inhibits the diffusion process (on regular graphs), 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.

Economic Value of User Localization in Wireless Networks

The defining characteristic of wireless and mobile networking is user mobility, and related to it is the ability for the network to capture (at least partial) information on where users are located and how users change location over time. Information about location is becoming critical, and therefore valuable, for an increasingly larger number of location-based or location-aware services. A key open question, however, is how valuable exactly this information is. Our goal in this paper is to help understand and estimate the economics, or the value of location information.

In a joint work with J. Bolot, [99], we addressed in particular the value of different granularities of location information, for example how much more valuable is it to know the GPS location of a mobile user compared to only knowing the access point, or the cell tower, that the user is associated with. We made three main contributions. First, we presented novel models, which capture the location-based economic activity of mobile users. Second, we derived closed-form analytic solutions for the economic value generated by those users. Third, we augmented the models to consider uncertainty about the users' location, and derived expressions for the economic value generated with different granularities of location information.

2.8.4 Collaborations

- Jean Bolot [SPRINT ATL]: [63], [62], [60], [72], [59], [99].
- Moez Draief [Imperial College London]: [64].

2.8.5 External support

Grant from SPRINT.

2.8.6 Self assessment

- Weak points: this line of research is a very interdisciplinary field and does not fit into the 'standard' cursus of our students. It is then hard to attract them on these topics.
- Strong points: early positioning on a fast growing topic with publications in major EE conferences: INFOCOM (3), SIGMETRICS, Allerton and economics conferences: Workshop on the Economics of Information Security(2), European Association for Research in Industrial Economics (EARIE) Conference, Conference on The Economics of the Software and Internet Industries.

3 Knowledge dissemination

3.1 Publications

	2008	2009	2010	2011
PhD Thesis	2		2	4
H.D.R (*)	1			
Journal	6	8	8	13
Conference proceedings (**)	14	10	23	16
Book chapter				
Book (written)		3		
Book (edited)				
Patent	1			4
General audience papers		1	1	
Technical report				
Deliverable				

(*) HDR Habilitation à diriger des Recherches
(**) Conference with a program committee

Main journals used by the project team

1. Queueing Systems (5)
2. IEEE Transactions on Information Theory (4)
3. Advances/Journal of Applied Probability (3)
4. IEEE JSAC Journal of Selected Areas in Communications (3)
5. The Computer Journal (3)
6. IEEE Transactions on Networking (2),
7. Mathematics of Operations Research (2)
8. Performance Evaluation (2)

Other journals: Annales de l'Institut Henri Poincaré, Annals of Probability, Annals of Telecommunications, Cluster Computing, Discrete Event Dynamic Systems, EURASIP Journal on Wireless Communications and Networking, European Transactions on Telecommunications, IEEE Transactions on Communications, IEEE Communications Letters, Journal of Statistical Physics, Markov Processes and Related Fields, Mathematical Methods in Operations Research, Numerical Linear Algebra with Applications, Random Structures and Algorithms, SIAM Journal on Computing, Stochastic Models.

Main conferences used by the project team

1. IEEE Infocom (13)
2. IEEE WiOpt (5)
3. IEEE ISIT (4)
4. European Wireless Conference (4)

5. ACM Sigmetrics (3)
6. Allerton Conference (3)
7. IEEE ICC (3)
8. ACM/ICST Valuetools (2)
9. ACM/SIAM SODA (2)
10. International Workshop on the Numerical Solution of Markov Chains (2)
11. IEEE ITST [International Conference on Telecommunications for Intelligent Transport Systems] (2)
12. QEST [International Conference on Quantitative Evaluation of SysTems] (2)

Other conferences: ACM NetEcon, ComNet, Conference on The Economics of the Software and Internet Industries, EMSOFT, European Performance Engineering Workshop, IEEE CDC, IEEE DYSPAN, IEEE ITSC, IEEE SECON, IEEE VTC, IFIP Wireless Days Conference, IFIP WMNC, NetGCOOP, SIAM workshop on Analytic Algorithmics and Combinatorics, STACS, WCTT, WINE, WODES, Workshop on the Economics of Information Security.

3.2 Software

Gibbs' Sampler for the self optimization of cellular networks The work on the self optimization of cellular networks based on Gibbs' sampler carried out in the joint laboratory with Alcatel-Lucent, led to the development of a software prototype that was presented by C. S. Chen at the INRIA Alcatel-Lucent joint laboratory seminar in March 2010 and demonstrated at the Alcatel-Lucent Bell Labs Open Days in May 2010. It was also demonstrated in the LINCS opening ceremony in April 2011.

PSI2 The work on perfect sampling has been partially implemented in a software tool PSI2, in collaboration with MESCAL team [INRIA Grenoble - Rhône-Alpes].

SERT/UTRANDIM SERT (Spatial Erlang for Real Time services) was a software designed by M. Karray [Orange Labs, Issy] 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 Orange Labs and is now included in UTRANDIM, a current dimensioning tool of Orange Corporate for UMTS and LTE networks. Some part of this research has been undertaken under contract number CRE 46146063-A012 between INRIA and France Télécom.

VoD Layered Coding Control 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.

3.3 Valorization and technology transfert

3.4 Teaching

We describe below the teaching activities in 2011. The activities of the other years are somewhat similar.

ENS Paris
- Undergraduate course (master level, MMFAI) by M. Lelarge and J. Salez, on Information Theory and Coding (24h + 24h of exercise session).
- Course on Communication Networks (master level, MMFAI) 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, MMFAI) by F. Baccelli, A. Bouillard and P. Brémaud, on Random Structures and Algorithms (35h + 28h of exercise session).
- Undergraduate exercise session (master level, MMFAI) by A. Bouillard on formal languages, computability and complexity (28h).

ENS Cachan - Antenne de Bretagne
- Preparation to the oral exams of the agregation of mathematics (computer science option) by A. Bouillard (12h).

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 on the conception of algorithms and applications (Licence Informatique, 3rd year), A. Bušić (24h)

Université Paris 10
- Preparation to the *certification C2i* by A. Benabid (36h)

Université de Versailles Saint-Quentin-en-Yvelines
- Graduate course on simulation (M2 COSY), A. Bušić (6h).

Below, we decribe tutorial activities on our research:

- Ecole de Recherche ENS Lyon 10-14 janvier 2011. 25 hours of lectures on stochastic geometry.
- Kyoto University, January 2011, Department of Systems Science, 3 lectures on "Stochastic Geometry and Wireless Networks".
- Chinese University of Hong Kong, July 2011, EECS Dept., 3 lectures on "Stochastic Geometry and Information Theory".
- Fields Mitacs Workshop "Probabilistic Methods in Wireless Networks", August 2011, http://www.fields.utoronto.ca/programs/scientific/11-12/wirelessnet/. 2 lectures on "Stochastic Geometry and Wireless Networks".
- Lectures on Clustering, percolation and convex ordering of point processes were taught during Summer Academy on "Stochastic Analysis, Modelling and Simulation of Complex Structures", Söllerhaus, Austria, September 2011 (4 hours); http://www.uni-ulm.de/mawi/summer-academy-2011/.

- A course on “Stochastic geometry and wireless networks” was taught at the 3rd Euro-NF Summer School on Opportunistic Networking, Valencia (Spain), June/July 2010, http://euronf.enst.fr/p_en_Events_Events2010_Summerscho_420.html and http://www.girba.upv.es/summerschool/.
- Tutorial of the Fourth EPFL-UPEMLV Workshop on Random Matrices, Information Theory and Applications: "Spectra of diluted random graphs", December 2010. http://ipg.epfl.ch/~leveque/EPFL_UPEMLV_Workshop/index.html.
- A Short Course on Palm Theory for Point Processes, was taught at the University of Milan, Italy (October 2009, 10H).
- A Short Course on Stochastic Geometry and Wireless Networks was taught at the University of California Berkeley, USA (September–October 2009, 8H).
- A tutorial was given at the summer school *ResCom2009* (La Palmyre, 7-12 June 2009; http://rescom09.isae.fr).
- “Cours de rentrée de la majeure de mathématiques de l’école polytechnique”, Hyères, September 08.

3.5 General Audience Actions

M. Lelarge gave a presentation on "Transmission fiable et codes correcteurs" for the Olympiades de mathématiques de l’Académie de Versailles 2010.

C.S. Chen presented the work of TREC on the self optimization of cellular networks based on Gibbs’ sampler at the INRIA Alcatel-Lucent joint laboratory seminar in March 2010 and organized a demonstration of a prototype at the Alcatel-Lucent Bell Labs Open Days in May 2010.

F. Baccelli wrote a survey article on the future of communication network for Annales des Mines [30] and a survey with Jon Crowcroft [Cambridge] for ERCIM News [19].

F. Baccelli organized the first *Séance publique sur les sciences de l’information* held by the French Academy of Sciences, Paris January 2008 http://www.academie-sciences.fr/video/v091007.htm.

F. Baccelli was chairman of the think tank “Internet du Futur” commissioned by Direction Générale des Entreprises.

3.6 Visibility

TREC was selected for the inria@siliconvalley program (2011-13). The partners are the EECS Department of the University of California Berkeley (Venkat Anantharam, Anant Sahai, David Tse) and the EE department of Stanford University (Abbas El Gamal). http://www.di.ens.fr/~baccelli/IT_SG_WN_web_site.htm The activity is centered on the inter-play between stochastic geometry and network information theory.

Emilie Coupechoux and Marc Lelarge got the best paper award of NetGCOOP 2011: International conference on NETwork Games, COntrol and OPtimization for their paper “Impact of Clustering on Diffusions and Contagions in Random Networks” [107].

The paper [67] on opportunistic scheduling in OFDMA cellular networks with fading got the best paper award of ComNet in 2009.

The paper [79] on the shadowing in cellular networks got the best paper award of WMNC in 2010.

We published two volume book [1, 2] on the use of the stochastic geometry framework for the modeling of wireless communications, which is becoming a reference monograph for this domain.

The 2009 survey paper [26] describing the general methodology followed by TREC on the use of stochastic geometry for the design and analysis of wireless networks received the best tutorial paper award of the Communication Society of IEEE for 2010.

TREC co-founded 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. The LINCS was officially launched by Ms Valérie Pécresse, who was then the French Minister of Research, on May 2nd, 2011.

F. Baccelli was co-organizer of the 6 month program entitled “Stochastic Processes and Communication Sciences” at the Isaac Newton Institute for Mathematical Sciences, Cambridge, UK. This programme aimed at the exposition of the latest developments in mathematical sciences lying on the boundary between the disciplines of stochastics and communications. The programme was attended by 87 long-term participants and 23 short-stay ones, and consisted of six international workshops.

Pierre Brémaud received in 2009 the “Grand Prix France Télécom” of the French Academy of Science.

TREC organized the Stochastic Networks’08 Conference at ENS Paris in June 2008, jointly with Jean Mairesse [LIAFA, Paris].

4 External Funding

(k euros)	2008	2009	2010	2011
INRIA Research Initiatives				
ARC† OCOQS				**17**
National initiatives				
ANR Cmon	**25**	**25**	**25**	**8**
European projects				
NoE EuroNF	8	8	8	8
EIT ICT				30
subtotal	**8**	**8**	**8**	**38**
Associated teams				
EA IT-SG-WN				**10**
Industrial contracts				
ALU	17	48	71	45
EADS	40	34	46	20
France Telecom			23	23
Sprint	25	25	25	25
Technicolor	15	15		6
subtotal	**97**	**122**	**165**	**113**
Scholarships				
PhD *	126	180	198	144
Post Doc*			16	72
subtotal	**126**	**180**	**214**	**216**
Total	**256**	**335**	**412**	**392**

† INRIA Cooperative Research Initiatives
∗ other than those supported by one of the above projects

The scholarships of the table come from ENS and from other universities and grandes écoles.

ARCs

ARC OCOQS Two-year ARC "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.

National initiatives

ANR CMON (2007–2010) http://wiki.grenouille.com/index.php/CMON jointly with Technicolor, 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.

ANR PEGASE "Performances guarantees pour les systèmes embarqués communiquants" (2010–2012) jointly with ENS Lyon, the INRIA project-team MESCAL, ONERA, Real-Time-at-Work (start-up) and Thalès; http://sites.onera.fr/pegase/. This project is focused on the analysis of critical embedded networks using algebraic tools.

ANR MAGNUM "Méthodes Algorithmiques pour la Génération aléatoire Non Uniforme: Modèles et applications" (2010–2014), jointly with LIP6, LIAFA, IGM, http://www-apr.lip6.fr/anrMagnum/.

GdR Stochastic Geometry TREC has participated in the mounting of the Research Group (Groupement de recherche, GdR) on Stochastic Geometry led by Pierre Calka (Université de Rouen); http://gdr-geostoch.math.cnrs.fr/ This GdR is going to be a collaboration framework for all French research teams working in the domain of *spatial stochastic modeling*, both on theory development and in applications. This year the application has been accepted by the National Committee of CNRS and the group will be officially created in 2012.

PEPS INS2I MonoSimPa Exploratory research (Projet Exploratoire Premier Soutien (PEPS)) of INS2I CNRS titled "Simulation Temps Paralléle, Simulation Parfaite et Monotonie" (MonoSimPa) is a one year exploratory project on parallel and perfect simulation. It is a joint project with PRiSM, Versailles (UMR 8144) and LIG, Grenoble (UMR 5217).

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 and officially launched in 2011. LINCS institutional members are: INRIA, Institut Télécom and UPMC. Alcatel-Lucent joined the LINCS in February 2011 as a strategic partner.

Digiteo project ACRON " Analyse et Conception de Réseaux Sans Fil Auto-Organisés" started in 2011. http://www.digiteo.fr/download/code_bt6ge67w0j Coordinator: Supélec (Télécommunications), Partners: Inria HIPERCOM, Université Paris-Sud, IEF. Trec is associated partner. The objectives are 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.

European projects

European Network of Excellence (NoE) Euro-NF http://euronf.enst.fr/en_accueil.html; (2008–2012) Coordinator: D. Kofman (Institut Télécom); about 30 partners. 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.

Stochastic Processes and Communication Sciences — 6 month program in 2010 co-organized by F. Baccelli at the Isaac Newton Institute for Mathematical Sciences, Cambridge, UK aiming at the exposition of the latest developments in mathematical sciences lying on the boundary between the disciplines of stochastics and communications. It brought together experts in the fields of probability and communications in order to review and further develop knowledge and trends; http://www.newton.ac.uk/programmes/SCS/index.html

EIT ICT Labs Project FUN “Fundamentals of Networking” (action line “Internet Technologies and Architectures”) 2011; Coordinator: INRIA TREC, Partners: INRIA GANG, VTT, Aalto University, Eindhoven University. http://eit.ictlabs.eu/ict-labs/all-events/article/fundamentals-of-future-networking-workshop/ The aim of this project is to build a community of researchers focusing on fundamental theoretical issues of future networking, including such topics as communication theory, network information theory, distributed algorithms, self-organization and game theory, modeling of large random and complex networks and structures.

Associated teams and other international projects

Associate team IT-SG-WN “Information Theory, Stochastic Geometry, Wireless Networks” (2011–2013) Partners: Inria-Trec, EECS Department University of California http://www.inria.fr/en/teams/it-sg-wn The activity of this proposal is centered on the interplay between stochastic geometry and network information theory, with 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. See also http://www.di.ens.fr/~baccelli/IT_SG_WN_web_site.htm

Associate Lab Inria-University of Melbourne, group of Darryl Veitch. (2006–2008) for developing our joint research action on active probing in the Internet.

Industrial contracts

Research Contract with Alcatel Bell “Choking of UDP traffic” (2007–2009) Project realized by Network Strategy Group of Alcatel Antwerp (Danny de Vleeschauwer and Koen Laevens) with N2NSoft (Laurent Fournié and Dohy Hong) 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, based on the theory of Markov decision processes, of optimal choking policies for the transport of layer encoded video in such an access networks.

Research Grant of Thomson Long term collaboration with the Paris Lab of Thomson (currently Technicolor) since its creation in 2006 by C. Diot and the arrival of L. Massoulié materialized into several joint seminars and reading groups, notably the Paris-Networking series (http://www.paris-networking joint courses and long term invitations (e.g. V. Anantharam from Berkeley and D. Veitch from Melbourne).

Sprint ATL Grant Long term collaboration (2006–2010) with Sprint ATL, in Burlingame, California recently focused on Bayesian inference to locate mobiles in cellular networks and The analysis of the economics of communication networks.

Scientific partnership with EADS CCR “Action de Partenariat Informatique Fondamentale” between ENS and EADS CC (2006–2010), This action allowed TREC to hire in 2007 a PhD student. The thesis, defended in November 2010, bore on the stochastic comparison of random measures, point process and shot-noise fields.

CRE with Orange Labs in 2010. The objective was to study the impact of the shadowing on the quality of service perceived by the users in wireless cellular networks.

CIFRE (PhD funding) grant of Technicolor started in 2011. 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.

5 Objectives for the next four years

5.1 Scientific Focus

The scientific focus of the future EPI will be on geometric network dynamics arising in communications.

By geometric networks we understand networks with a nontrivial, discrete or continuous, geometric definition of the existence of links between the nodes. In stochastic geometric networks, this definition leads to random-graphs or stochastic-geometric models.

A first type of geometric network dynamics is that where the nodes or the links changes over time according to an exogeneous dynamics (e.g. node motion and geometric definition of the links). We will refer to this as "dynamics of geometric networks" below. A second type is that where links and/or nodes are fixed but harbor local dynamical systems (in our case, stemming from e.g. information theory, queuing theory, social and economic sciences). This will be called "dynamics on geometric networks". A third type is that where the dynamics of the network topology and the local dynamics interplay.

Our motivations for studying these systems stem from many fields of communications where such problems are central and in particular: message passing algorithms; epidemic algorithms; wireless networks and information theory; device to device networking; distributed content delivery; social and economic networks.

We will develop the 3 axes outlined above and described in mode detail in subsections 1.1-1.3 below.

5.1.1 Dynamics of Geometric Networks.

Networks are rarely static and their structures evolve over time (mobility in wireless communication networks, network formation models, evolving population of nodes ...), which further complicates the analysis of network algorithms and poses challenging problems of independent interest: 1) Preferential attachment defines a dynamics on a graph based on its local topological properties and has been used to explain the graph of connections between autonomous systems in the Internet and on which communications are then routed. 2) The correlation of user mobility, in everyday life or in social events like "Fête de la Musique" in Paris, feature random hot-spot or flash-crowd dynamics in the Euclidean space that have to be understood in order to design/adapt the cellular networks serving these users.

5.1.2 Dynamics on Geometric networks.

The dynamics of network algorithms (basic communication algorithms, epidemics, algorithms representing social or economic interactions, consensus and other message passing algorithms) is determined by the (either continuous or discrete) structure of the underlying geometric network. Here are a few basic examples: 1) The gain matrix in a wireless network is an Euclidean geometry object which determines the achievable bit rates/flows of its links. 2) The adjacency matrix of the underlying routing graph in a queuing network, together with the packet sizes and the routing mechanism, determine the dynamics of packets and hence the global behavior of this network. 3) The convergence properties of a message passing algorithm is determined by the discrete geometry of the graph on which it is defined. 4) The properties of the execution of an epidemic algorithm ot the spreading of a tweet, are determined by the discrete geometry of the underlying graph (the follower graph in the twitter case).

5.1.3 Interplay between Dynamics on and of Geometric Networks.

Some of the most challenging problems are those where the geometric network structure is influenced by the way its components dynamically interact. Here are a few typical examples: 1) Medium access protocols aim at dynamically scheduling wireless links in such a way that appropriate exclusion areas hold around receivers at any given scheduling step. Similarly, scheduling policies for Internet switches need to find matchings in the bipartite graph of input and output ports in order to maximize throughput. 2) Social and economic networks define communities by associating peers with similar interests, namely close-by in some semantic space, through evolutionary mechanisms: the existence of links between two nodes depends on their past interactions (nodes tend to interact with friends, or nodes with whom the past interactions were profitable ...). In such cases, the network is built both to learn from the neighbors and to have economic interaction with them. In mechanism design, the algorithm designer should ensure that the resulting dynamics is correct, i.e. that the agents' interests are best served by behaving nicely. 3) Neighborhoods play a key role for defining peering patterns in distributed content delivery networks. But nearby peers exchange data at a higher rate and vanish faster from the network.

In all the cases described above, the geometry of the network and its dynamics are viewed as constraints for the algorithm. In some cases, the paradigm is actually inverted: for a given simple algorithm, the challenge is to design a geometric network on which the dynamics of the algorithm is known to behave nicely. For example, the design of good error-correcting codes (i.e. easy to decode) or good sampling techniques for sparse signals (i.e. allowing to reconstruct the initial signal) can be cast as a problem of designing a high-dimensional geometric structure on which the (decoding or reconstruction) algorithm will have a short runtime.

This line of thought has hardly been formalized and will require the development of new mathematical tools that go way beyond what has been done so far in such frameworks as time-space statistics, cellular automata, network games, stochastic geometry or random graph theory, where either the geometry or the dynamics are too simplistic for addressing the problems identified above.

5.2 Scientific Context

This plan clearly leverages the major strengths of the involved researchers.

The group of researchers has strong records in communication network analysis and design, which is a common feature to all researchers of the EPI.

The group of researchers has strong methodological credentials in discrete event dynamical systems (queuing theory and network calculus), in static stochastic geometry (for both wireline and wireless networks) and in random graphs.

Until now, the research activities on discrete event dynamical systems are somewhat separated from those on random graphs and stochastic geometry. In addition, the latter have been focused on spatial averages and static analysis and did not really start investigating dynamics.

This new research programme will hence require significant inflection of the activities of the involved researchers. The core of the future mathematical activity will be based on the deepening of these three domains and on their convergence towards the development of new tools for time-space networking.

5.3 Interfaces

5.3.1 Structural Interfaces

We intend to keep and develop our two current affiliations: ENS and LINCS.

- The interplay with ENS will be deepened in the direction of teaching and of the shaping of the maths-CS interface. We will also benefit from interactions with the physics department (laboratoire de physique théorique) and in particular with members having a strong empirical expertise in message-passing algorithms.

- The interplay with LINCS is essential to us. It allows the structuring of a stable engineering interface (Bell Labs) and the shaping of a community of researchers on communication networks with the critical mass. This will will benefit from interactions with members of EPI Gang and Telecom ParisTech on Content Delivery and of UPMC on Network Probing.

5.4 Other EPIs

There are groups working on graph algorithms for communications (e.g. Gang, Mascotte) but not really on dynamical systems on such objects. We do intend to deepen the collaboration with Gang which already resulted in joint research on Distributed Content Delivery lately.

There are groups working on various aspects of network science (Maestro, Rap, Dyonisos, Mescal), but we see none of them focusing on anything close to what we propose. We collaborate with Maestro (on the interface between stochastic geometry and game theory and on MDP) and with Mescal (on discrete event dynamical systems).

There are several groups working on specific domains of wireless communications (Hipercom on Mobile ad Hoc Networks, Swing on collaborative schemes in wireless). Our focus, on wireless, will be on the mathematical modeling of time-space wireless networking, which we see as complementary to what these EPIs do. We have been collaborating on wireless stochastic geometry with Hipercom for a long time. We also collaborate with Swing.

5.4.1 Other Groups in France

There are a few maths groups in France working on Stochastic Geometry (e.g. P. Calka) or on random graphs or random trees (e.g. J.F. Le Gall) but not with the "communication network" focus. We intend to structure the interactions with these groups through the new GDR on stochastic geometry just created by P. Calka and the GDR IM of B. Vallée.

5.4.2 Industrial Interfaces

The group of researchers has had effective impact on the design or the operation of industrial products and architectures (Alcatel's DSLAM, Orange's UMTS network, Alcatel-Lucent's distributed optimization algorithms, Qualcomm's FlashLinq) and will continue this line of action in the application fields listed above. The main current interfaces are Alcatel Lucent, Technicolor, Qualcomm and Orange. So far, the funding of TREC has been significantly more through industrial grants than through European or National projects.

5.4.3 International Groups

There are some common aims with the 'Random Spatial Structures' Program at EURANDOM, led by Pr. R. van der Hofstad. The focus of this group is more on theoretical physics while our group will focus on communication networks. There is also some overlap with groups at MIT (D. Shah, D. Gamarnik) but they have much less emphasis on geometric networks. We are actively collaborating with groups having a related focus in UC Berkeley (V. Anantharam, D. Tse of the Wireless Foundations Center of ECE, on information theory and wireless networks) and Stanford U. (with A. Montanari on compressed sensing and A. El Gamal on network Information Theory).

6 Bibliography of the project-team

Books and Monographs

[1] François Baccelli and Bartłomiej Błaszczyszyn. *Stochastic Geometry and Wireless Networks, Volume I — Theory*, volume 3, No 3–4 of *Foundations and Trends in Networking*. NoW Publishers, 2009.

[2] François Baccelli and Bartłomiej Błaszczyszyn. *Stochastic Geometry and Wireless Networks, Volume II — Applications*, volume 4, No 1–2 of *Foundations and Trends in Networking*. NoW Publishers, 2009.

[3] Pierre Brémaud. *Initiation aux Probabilites et aux chaines de Markov*. Springer-Verlag, 2009.

Doctoral Dissertations and "Habilitation" Theses

[4] Bartolomiej Błaszczyszyn. *Stochastic Geometry Methods and their Applications in Queueing and Telecommunications*. Habilitation à diriger des recherches, Department of Mathematics and Computer Science, University of Wrocław, Poland, October 2008.

[5] Giovanna Carofiglio. *Flow-level Stochastic Analysis and Fluid Modelling of TCP/IP networks*. PhD thesis, Politecnico di Torino and Telecom Paris Tech, April 2008.

[6] Huu Quinh Nguyen. *Réseaux Sans Fil Hybrides WiFi–WiMax*. PhD thesis, Telecom Paris Tech, March 2008.

[7] Paola Bermolen. *Modèles Probabilistes et Statistiques pour la Conception et l'Analyse des Systèmes de Communications*. PhD thesis, Télécom ParisTech, France, February 2010.

[8] Dhandapani Yogeshwaran. *Stochastic geometric networks : connectivity and comparison*. PhD thesis, Université Pierre et Marie Curie, Paris, France., 2010.

[9] Hamed Amini. *Epidémies et Percolation dans les Graphes Aléatoires*. PhD thesis, Université Pierre et Marie Curie, Paris, France, 2011.

[10] Bruno Kauffmann. *Inverse Problems in Networks*. PhD thesis, Université Pierre et Marie Curie, Paris, France., 2011.

[11] Van Minh Nguyen. *Modélisation des Liens de Communication Radio et Optimisation de la Gestion de Mobilité dans les Réseaux Cellulaires*. PhD thesis, Télécom ParisTech, 2011.

[12] Justin Salez. *Quelques conséquences de la convergence locale faible pour les graphes aléatoires*. PhD thesis, Université Pierre et Marie Curie, Paris, France, 2011.

Articles in Refereed Journals

[13] David Aldous, Charles Bordenave, and Marc Lelarge. Near-minimal spanning trees: a scaling exponent in probability models. *Annales de l'Institut Henri Poincaré (B)*, 44(5):962–976, 2008.

[14] François Baccelli and David McDonald. A stochastic model for the throughput of non-persistent tcp flows. *Performance Evaluation*, 65(6-7):512–530, June 2008.

[15] Srikant K. Iyer, D. Manjunath, and Dhandapani Yogeshwaran. Limit laws of k-coverage of paths in Markov-Poisson-Boolean model. *Stochastic Models*, (Volume 24):558–582, 2008.

[16] Marc Lelarge. Packet reordering in networks with heavy-tailed delays. *Math. Methods Oper. Res.*, 67(2):341–371, 2008.

[17] Marc Lelarge. Tail asymptotics for discrete event systems. *Discrete Event Dynamic Systems*, 18(4):563–584, 2008.

[18] David J. Aldous, Charles Bordenave, and Marc Lelarge. Dynamic programming optimization over random data: the scaling exponent for near optimal solutions. *SIAM J. Comput.*, 38(6):2382–2410, 2009.

[19] François Baccelli and Jon Crowcroft. Future internet technology - introduction. *ERCIM News*, 2009(77), 2009.

[20] François Baccelli, Sridhar Machiraju, Darryl Veitch, and Jean Bolot. The role of pasta in network measurement. *IEEE/ACM Trans. Netw.*, 17(4):1340–1353, 2009.

[21] François Baccelli, Bartlomiej Błaszczyszyn, and Paul Mühlethaler. Stochastic analysis of spatial and opportunistic Aloha. *IEEE JSAC, special issue on Stochastic Geometry and Random Graphs for Wireless Networks*, 27:1105–1119, 2009.

[22] François Baccelli, Giovanna Carofiglio, and Sergey Foss. Split tcp: Dynamics, stability and tail asymptotics. *From Semantics to Computer Science, Essays in Honour of Gilles Kahn*, 2009.

[23] François Baccelli, Bruno Kauffmann, and Darryl Veitch. Inverse problems in queueing theory and internet probing. *Queueing Systems*, 63:59–107, 2009.

[24] François Baccelli, Bruno Kauffmann, and Darryl Veitch. Towards multihop available bandwidth estimation. *ACM SIGMETRICS Performance Evaluation Review*, 37:83–84, 2009.

[25] Bartlomiej Błaszczyszyn and Dhandapani Yogeshwaran. Directionally convex ordering of random measures, shot-noise fields and some applications to wireless networks. *Adv. Appl. Probab.*, 41:623–646, 2009.

[26] Martin Haenggi, Jeffrey G. Andrews, François Baccelli, Olivier Dousse, Massimo Franceschetti, and Donald F. Towsley. Guest editorial: Geometry and random graphs for the analysis and design of wireless networks. *IEEE Journal on Selected Areas in Communications*, 27(7):1025–1028, 2009.

[27] Marc Lelarge. Asymptotic behavior of generalized processor sharing queues under subexponential assumptions. *Queueing Syst.*, 62(1-2):51–73, 2009.

[28] Justin Salez and Devavrat Shah. Belief propagation: an asymptotically optimal algorithm for the random assignment problem. *Mathematics of Operations Research*, 34:468–480, 2009.

[29] Hamed Amini. Bootstrap percolation in living neural networks. *Journal of Statistical Physics*, 141:459–475, 2010.

[30] François Baccelli. Les réseaux de communication du futur. *Annales des Mines*, pages 5–9, November 2010.

[31] François Baccelli, Bartłomiej Błaszczyszyn, and P. Mühlethaler. Time-space opportunistic routing in wireless ad hoc networks, algorithms and performance. *The Computer Journal*, 53(5):592–609, 2010.

[32] Florence Bénézit, Dimakis, Alexandros, G., Patrick Thiran, and Martin Vetterli. Order-Optimal Consensus Through Randomized Path Averaging. *IEEE Trans. on Information Theory*, 56(10), 2010.

[33] Charles Bordenave and Marc Lelarge. Resolvent of large random graphs. *Random Struct. Algorithms*, 37(3):332–352, 2010.

[34] Pierre Brémaud and Serguei Foss. Ergodicity of a stress release point process seismic model with aftershocks. *Markov Processes and Related Fields*, 16(2):389–408, 2010.

[35] Van Minh Nguyen, François Baccelli, Laurent Thomas, and Chung Shue Chen. Best signal quality in cellular networks: asymptotic properties and applications to mobility management in small cell networks. *EURASIP Journal on Wireless Communications and Networking*, 2010:1–14, 2010.

[36] Furcy Pin, Darryl Veitch, and Bruno Kauffmann. Statistical estimation of delays in a multicast tree using accelerated em. *Queueing Systems*, 66:369–412, 2010.

[37] K. Shum, W. S. Wong, and Chung Shue Chen. A general upper bound on the size of constant-weight conflict-avoiding codes. *IEEE Transactions on Information Theory*, 56(7):3265–3276, 2010.

[38] Jeffrey Andrews, François Baccelli, and Radhakrishna Ganti. Tractable approach to coverage and rate in cellular networks. *IEEE Transactions on Communications*, 59(11):3122–3134, 2011.

[39] François Baccelli, Nicholas Bambos, and Nicolas Gast. Distributed delay-power control algorithms for bandwidth sharing in wireless networks. *IEEE/ACM Trans. Netw.*, 19(5):1458–1471, 2011.

[40] François Baccelli, Abbas El Gamal, and David Tse. Interference networks with point-to-point codes. *IEEE Transactions on Information Theory*, pages 2582–2596, 2011.

[41] François Baccelli, Sridhar Machiraju, Darryl Veitch, and Jean Bolot. Probing for loss: The case against probe trains. *IEEE Communications Letters*, 15(5):590–592, 2011.

[42] François Baccelli, Bartlomiej Blaszczyszyn, and Mir Omid Haji Mirsadeghi. Optimal Paths on the Space-Time SINR Random Graph. *Advances in Applied Probability*, 43(1):131–150, 2011.

[43] François Baccelli and Serguei Foss. Poisson hail on a hot ground. *Journal of Applied Probability*, 48(1), 2011.

[44] Bartlomiej Blaszczyszyn and Mohamed Kadhem Karray. Effect of Opportunistic Scheduling on the Quality of Service Perceived by the Users in OFDMA Cellular Networks. *Annals of Telecommunications*, 2011.

[45] Charles Bordenave, Marc Lelarge, and Justin Salez. The rank of diluted random graphs. *Ann. Probab.*, 39(3):1097–1121, 2011.

[46] Ana Bušić and Jean-Michel Fourneau. Iterative component-wise bounds for the steady-state distribution of a Markov chain. *Numerical Linear Algebra with Applications*, 18(6):1031–1049, 2011.

[47] Chung Shue Chen, K. Shum, and C. W. Sung. Round-robin power control for the sum rate maximization of wireless networks. *European Transactions on Telecommunications*, pages 1–13, 2011.

[48] Tien Viet Nguyen and François Baccelli. A stochastic geometry model for cognitive radio networks. *The Computer Journal*, 2011.

[49] Ana Bušić and Jean-Michel Fourneau. Monotonicity and performance evaluation: applications to high speed and mobile networks. *Cluster Computing*, April 2011.

Publications in Conferences and Workshops

[50] Venkat Anantharam and François Baccelli. A Palm theory approach to error exponents. In *Proceedings of the 2008 IEEE Symposium on Information Theory*, Toronto, Canada, July 2008.

[51] François Baccelli, Bartlomiej Błaszczyszyn, Erwan Ermel, and Paul Mühlethaler. An optimized relay self selection technique for opportunistic routing in mobile ad hoc networks. In *Proc. of IEEE European Wireless Conference*, Prague, June 2008.

[52] François Baccelli, Bartlomiej Błaszczyszyn, and Paul Mühlethaler. On the performance of time-space opportunistic routing in multihop mobile ad hoc networks. In *Proc. of IEEE WiOpt*, Berlin, April 2008.

[53] François Baccelli, Giovanna Carofiglio, and Serguei Foss. Proxy caching in split TCP: Dynamics, stability and tail asymptotics. In *Proc. of IEEE INFOCOM*, Phoenix, Arizona, April 2008.

[54] Bartlomiej Błaszczyszyn and Mohamed K. Karray. An efficient analytical method for dimensioning of cdma cellular networks serving streaming calls. In *Proc. of ACM/ICST VALUETOOLS*, Athens, Greece, October 2008.

[55] Bartlomiej Błaszczyszyn and Mohamed K. Karray. Impact of mean user speed on blocking and cuts of streaming traffic in cellular networks. In *Proc. of European Wireless Conference*, Prague, June 2008.

[56] Bartłomiej Błaszczyszyn, Anis Laouiti, Paul Muhlethaler, and Yasser Toor. Comparison for VANETs: conventional routing vs an advanced opportunistic routing scheme using active signaling. In *Proc. of ITST*, Phuket, Thailand, November 2008.

[57] Bartłomiej Błaszczyszyn, Anis Laouiti, Paul Muhlethaler, and Yasser Toor. Opportunistic broadcast in VANETs (OB-VAN) using active signaling for relays selection. In *Proc. of ITST*, Phuket, Thailand, November 2008.

[58] Bartlomiej Błaszczyszyn and Bozidar Radunović. Using transmit-only sensors to reduce deployment cost of wireless sensor networks. In *Proc. of IEEE INFOCOM*, Phoenix, AZ, 2008.

[59] Jean Bolot and Marc Lelarge. Cyber insurance as an incentive for internet security. In *Proc. of Workshop on the Economics of Information Security (WEIS)*, June 2008.

[60] Jean Bolot and Marc Lelarge. A new perspective on internet security using insurance. In *Proc of IEEE INFOCOM*, pages 1948–1956, April 2008.

[61] Marc Lelarge. Diffusion of innovations on random networks: Understanding the chasm. In *Proc. of WINE 08*, pages 178–185, 2008.

[62] Marc Lelarge and Jean Bolot. A local mean field analysis of security investments in networks. In *Proc. of ACM SIGCOMM workshop NetEcon'08*, pages 25–30, 2008.

[63] Marc Lelarge and Jean Bolot. Network externalities and the deployment of security features and protocols in the internet. In *Proc. of ACM SIGMETRICS '08*, pages 37–48, New York, NY, USA, 2008.

[64] Hamed Amini, Moez Draief, and Marc Lelarge. Network control and optimization. chapter Marketing in a Random Network, pages 17–25. Springer-Verlag, Berlin, Heidelberg, 2009.

[65] François Baccelli, Giovanna Carofiglio, and Marta Piancino. On scalable tcp. In *Proc. of IEEE INFOCOM*, Rio de Janeiro, Brazil, 2009.

[66] Bartlomiej Błaszczyszyn and Mohamed K. Karray. Dimensioning of the downlink in OFDMA cellular networks via an erlang's loss model. In *Proc. of European Wireless Conference*, Aalborg, 2009.

[67] Bartlomiej Błaszczyszyn and Mohamed K. Karray. Fading effect on the dynamic performance evaluation of OFDMA cellular networks. In *Proc. of the 1st International Conference on Communications and Networking (ComNet)*, 2009.

[68] Bartlomiej Błaszczyszyn, Paul Mühlethaler, and Yasser Toor. Maximizing throughput of Linear Vehicular Ad-hoc NETworks (VANETs) — a stochastic approach. In *Proc. of European Wireless Conference*, Aalborg, 2009.

[69] Bartlomiej Błaszczyszyn, Paul Mühlethaler, and Yasser Toor. Performance of mac protocols in linear VANETs under different attenuation and fading conditions. In *Proc. of IEEE ITSC*, St. Louis, MO, USA, 2009.

[70] Marc Lelarge. Economics of malware: Epidemic risks model, network externalities and incentives. In *Fifth bi-annual Conference on The Economics of the Software and Internet Industries*, 2009.

[71] Marc Lelarge. Efficient control of epidemics over random networks. In *Proceedings of SIGMETRICS/Performance*, pages 1–12, 2009.

[72] Marc Lelarge and Jean Bolot. Economic Incentives to Increase Security in the Internet: The Case for Insurance. In *Proc. of IEEE INFOCOM*, Rio de Janeiro, Brazil, 2009.

[73] Justin Salez and Devavrat Shah. Optimality of belief propagation for the random assignment problem. In *ACM-SIAM Symposium on Discrete Algorithms (SODA)*, 2009.

[74] Jeffrey Andrews, François Baccelli, and Radhakrishna Ganti. A tractable approach to cellular network modeling. In *The 48th Allerton conference on communication, control and computing.*, University of Illinois at Urbana-Champaign, 2010.

[75] François Baccelli and Bartłomiej Błaszczyszyn. A new phase transition for local delays in MANETs. In *Proc. of IEEE INFOCOM*, San Diego CA, 2010.

[76] Florence Bénézit, Vincent Blondel, Patrick Thiran, John Tsitsiklis, and Martin Vetterli. Weighted Gossip: Distributed Averaging Using Non-Doubly Stochastic Matrices. In *Proc. of ISIT*, 2010.

[77] Albert Benveniste, Anne Bouillard, and Paul Caspi. A unifying view of loosely time-triggered architectures. In *Proc. of EMSOFT*, pages 189–198, 2010.

[78] Paola Bermolen and François Baccelli. Multiple access mechanisms with performance guarantees for ad-hoc networks. In *Proc. of the 7th Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks (SECON)*, Boston, USA, 2010. doi 10.1109/SECON.2010.5508198.

[79] Bartłomiej Błaszczyszyn, M. K. Karray, and François-Xavier Klepper. Impact of the geometry, path-loss exponent and random shadowing on the mean interference factor in wireless cellular networks. In *Proc. of IFIP WMNC*, Budapest, Hungary, 2010.

[80] Bartłomiej Błaszczyszyn and Paul Mühlethaler. Stochastic analysis of non-slotted Aloha in wireless ad-hoc networks. In *Proc. of IEEE INFOCOM*, San Diego, CA, 2010.

[81] Bartłomiej Błaszczyszyn, Paul Mühlethaler, and Skander Banaouas. Coexistence of radio networks using Aloha. In *Proc. of IFIP Wireless Days Conference*, Venice, Italy, 2010.

[82] Bartłomiej Błaszczyszyn and D. Yogeshwaran. Connectivity in sub-poisson networks. In *The 48th Allerton conference on communication, control and computing.*, University of Illinois at Urbana-Champaign, 2010.

[83] Charles Bordenave and Marc Lelarge. The rank of diluted random graphs. In *Proc. fo SODA*, pages 1389–1402, 2010.

[84] Anne Bouillard, Laurent Jouhet, and Éric Thierry. Comparison of different classes of service curves in network calculus. In *Proc. of WODES*, pages 216–321, 2010.

[85] Anne Bouillard, Laurent Jouhet, and Eric Thierry. Tight performance bounds in the worst-case analysis of feed-forward networks. In *Proc. of IEEE INFOCOM*, pages 1316–1324, 2010.

[86] Ana Bŭsić, Hilal Djafri, and Jean-Michel Fourneau. Stochastic bounds for censored Markov chains. In *Proc. of 6th International Workshop on the Numerical Solution of Markov Chains (NSMC)*, Williamsburg, USA, 2010.

[87] Ana Bŭsić and Jean-Michel Fourneau. Iterative component-wise bounds for the steady-state distribution of a Markov chain. In *Proc. of 6th International Workshop on the Numerical Solution of Markov Chains (NSMC)*, Williamsburg, USA, 2010.

[88] Ana Bŭsić and Jean-Michel Fourneau. A toolbox for component-wise bounds of the steady-state distribution of a dtmc. In *Proc. of International Conference on Quantitative Evaluation of Systems (QEST)*, Williamsburg, USA, 2010.

[89] Ana Bŭsić, Bruno Gaujal, Gael Gorgo, and Jean-Marc Vincent. PSI2 : Envelope perfect sampling of non monotone systems. In *Proc. of International Conference on Quantitative Evaluation of Systems (QEST)*, Williamsburg, USA, 2010.

[90] Chung Shue Chen and François Baccelli. Self-optimization in mobile cellular networks: power control and user association. In *Proc. of IEEE ICC 2010*, pages 1–6, 2010.

[91] Frederic Morlot, François Baccelli, and S. Elayoubi. An interaction-based mobility model for dynamic hot spot analysis. In *Proc. of IEEE INFOCOM*, San Diego, CA, USA, 2010.

[92] Tien Viet Nguyen and François Baccelli. A probabilistic model of carrier sensing based cognitive radio. In *Proc. of 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum (DYSPAN)*, pages 1–12, 2010.

[93] Tien Viet Nguyen and François Baccelli. Stochastic modeling of carrier sensing based cognitive radio networks. In *Proc. of WiOpt/Spaswin*, pages 472–480, 2010.

[94] Van Minh Nguyen and Francois Baccelli. A stochastic geometry model for the best signal quality in a wireless network. In *Proc. of WiOpt/Spaswin*, pages 465–471, Avignon, France, 2010.

[95] Van Minh Nguyen and Holger Claussen. Efficient self-optimization of neighbour cell lists in macrocellular networks. In *Proc. IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications, PIMRC*, pages 1921–1926, Istanbul, Turkey, 2010.

[96] Hui Zang, François Baccelli, and J. Bolot. Bayesian inference for localization in cellular networks. In *Proc. of IEEE INFOCOM*, San Diego, CA, USA, 2010.

[97] Hamed Amini, Moez Draief, and Marc Lelarge. Flooding in weighted random graphs. In *SIAM workshop on Analytic Algorithmics and Combinatorics*, pages 1–15, 2011.

[98] F. Baccelli, A. El Gamal, and D. Tse. Interference networks with point-to-point codes. In *Information Theory Proceedings (ISIT), 2011 IEEE International Symposium on*, pages 435–439, July 2011.

[99] François Baccelli and Jean Bolot. Modeling the economic value of the location data of mobile users. In *Proc. of IEEE INFOCOM*, pages 1467–1475, 2011.

[100] François Baccelli, Junyi Li, Thomas Richardson, Sundar Subramanian, Xinzhou Wu, and Sanjay Shakkottai. On optimizing csma for wide area ad-hoc networks. In *Proc. of WiOpt/Spaswin*, pages 354–359, 2011.

[101] Éric Badouel, Anne Bouillard, Philippe Darondeau, and Jan Komenda. Residuation of tropical series: rationality issues. In *joint 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC'11)*, Orlanda, USA, December 2011. IEEE.

[102] Anne Bouillard. Composition of service curves in network calculus. In *first International Workshop on Worst-case Traversal Time (WCTT)*, Vienna, Austria, November 2011.

[103] Anne Bouillard and Aurore Junier. Worst-case delay bounds with fixed priorities using network calculus,. In *Fifth International Conference on Performance Evaluation Methodologies and Tools*, Cachan, France, May 2011.

[104] Ana Bušić and Emilie Coupechoux. Perfect sampling with aggregated envelopes. In *Proc. of 49th Annual Allerton Conference on Communication, Control, and Computing*, Monticello, IL, USA, 2011.

[105] Ana Bušić, Jean Mairesse, and Irene Marcovici. Probabilistic cellular automata, invariant measures, and perfect sampling. In *Proc. of 28th International Symposium on Theoretical Aspects of Computer Science, (STACS)*, pages 296–307, Dortmund, Germany, 2011.

[106] Chung Shue Chen, François Baccelli, and Laurent Roullet. Joint optimization of radio resources in small and macro cell networks. In *Proc. of IEEE VTC 2011*, pages 1–5, 2011.

[107] Emilie Coupechoux and Marc Lelarge. Impact of clustering on diffusions and contagions in random networks. In *Proceedings of NetGCOOP '11*, 2011.

[108] Radha Krishna Ganti, François Baccelli, and Jeffrey G. Andrews. A new way of computing rate in cellular networks. In *ICC*, pages 1–5, 2011.

[109] V. Garcia, Chung Shue Chen, N. Lebedev, and J.-M. Gorce. Self-optimized precoding and power control in cellular networks. In *Proc. of IEEE PIMRC 2011*, pages 1–5, 2011.

[110] Yuchul Kim, François Baccelli, and Gustavo de Veciana. Spatial reuse and fairness of mobile ad-hoc networks with channel-aware csma protocols. In *Proc. of WiOpt/Spaswin*, pages 360–365, 2011.

[111] Van Minh Nguyen, Chung Shue Chen, and Laurent Thomas. Handover Measurement in Mobile Cellular Networks: Analysis and Applications to LTE. In *Proceedings of 2011 IEEE International Conference on Communications (ICC)*, pages 1–6, Kyoto, Japan, June 2011. IEEE.

[112] Furcy Pin, Ana Bušić, and Bruno Gaujal. Acceleration of perfect sampling by skipping events. In *Proc. of 5th International ICST Conference on Performance Evaluation Methodologies and Tools (Valuetools)*, Cachan, France, 2011.

[113] Alexander Wieczorek, Ana Bušić, and Emmanuel Hyon. Critical level policies in lost sales inventory systems with different demand classes. In *Proc. of 8th European Performance Engineering Workshop (EPEW), LNCS 6977*, pages 204–218, Borrowdale, The English Lake District, UK, 2011. Springer-Verlag.

Reports

[114] M.K. Hanawal, E. Altman, and F. Baccelli. Stochastic geometry based medium access games in mobile ad hoc networks. to appear in the proceedings of Infocom'12.

[115] T.V. Nguyen and F. Baccelli. Generating functional of matern like point processes: From hard core to carrier sensing. to appear in the proceedings of Infocom'12.

[116] Venkat Anantharam and François Baccelli. Information–theoretic capacity and error exponents of stationary point processes under random additive displacements. Technical Report ArXiv:1012.4924v1, ArXiv, 2010. submitted to Adv. Appl. Probab.

[117] A. Bušić, V. Gupta, and J. Mairesse. Stability of the bipartite matching model. Research report, arXiv, 2010. Short version appeared in Proceedings of MAMA 2010.

[118] Marc Lelarge. Diffusion and cascading behavior in random networks. Research report, arXiv, 2010.

[119] François Baccelli, Fabien Mathieu, and Ilkka Norros. Performance of P2P Networks with Spatial Interactions of Peers. Research Report RR-7713, INRIA, August 2011.

[120] B. Błaszczyszyn and D. Yogeshwaran. Clustering and percolation of point processes. arXiv:1112.2227, 2011.

[121] B. Błaszczyszyn and D. Yogeshwaran. Clustering, percolation and directionally convex ordering of point processes. arXiv:1105.4293v1, 2011.

[122] B. Błaszczyszyn and D. Yogeshwaran. On comparison of clustering properties of point processes. arXiv:1111.6017, 2011.

[123] C. Bordenave, M. Lelarge, and J. Salez. Matchings on infinite graphs. Research report, ArXiv, February 2011.

[124] Anne Bouillard, Nadir Farhi, and Bruno Gaujal. Packetization and aggregate scheduling. Research report, Hal-Inria, 2011.

[125] Ana Bušić, Nazim Fatès, J. Mairesse, and Irene Marcovici. Density classification on infinite lattices and trees. Research report, arXiv, 2011. Short version accepted at LATIN 2012.

[126] Ana Bušić, Bruno Gaujal, and Furcy Pin. Perfect sampling of Markov chains with piecewise homogeneous events. Research report, arXiv, 2011. To appear in Performance Evaluation.

[127] Harpreet S. Dhillon, Radha Krishna Ganti, François Baccelli, and Jeffrey G. Andrews. Modeling and analysis of k-tier downlink heterogeneous cellular networks. *CoRR*, abs/1103.2177, 2011. to appear in IEEE JSAC.

[128] Radhakrishna Ganti, François Baccelli, and Jeffrey Andrews. Series expansion for interference in wireless networks. Research report, arXiv, 2011. to appear in IEEE Tr. Information Theory.

[129] Justin Salez. The cavity method for counting spanning subgraphs subject to local constraints. Research report, arXiv, 2011.

[130] Ana Bušić, Ingrid Vliegen, and Alan Scheller-Wolf. Comparing Markov chains: Aggregation and precedence relations applied to sets of states, with applications to assemble-to-order systems. *Mathematics of Operations Research*, 2012. to appear.

[131] Eitan Altman and Augustin Chaintreau, editors. *Network Control and Optimization, Second Euro-NF Workshop, NET-COOP 2008, Paris, France, September 8-10, 2008. Revised Selected Papers*, volume 5425 of *Lecture Notes in Computer Science*. Springer, 2009.

[132] François Baccelli, Junyi Li, Thomas Richardson, Sundar Subramanian, Xinzhou Wu, and Sanjay Shakkottai. On optimizing csma for wide area ad-hoc networks. *Queuing Systems*, To appear.

[133] François Baccelli and Paola Bermolen. Extremal versus additive matérn point processes. *Queuing Systems*, to appear.