Activity Report 2017

Project-Team DYOGENE

Dynamics of Geometric Networks

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

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Creation of the Project-Team: 2013 July 01

Keywords:

<u>**Computer Science and Digital Science:**</u>

A1.2.4. - QoS, performance evaluation
A6.1.4. - Multiscale modeling
A6.2.3. - Probabilistic methods
A8.1. - Discrete mathematics, combinatorics
A8.2. - Optimization
A8.3. - Geometry, Topology
A8.6. - Information theory
A8.7. - Graph theory
A8.8. - Network science
A8.9. - Performance evaluation
A9.2. - Machine learning
A9.7. - AI algorithmics

<u>**Other Research Topics and Application Domains:**</u>

B4.3. - Renewable energy production
B6.2.2. - Radio technology
B6.3.4. - Social Networks

1. Personnel

Research Scientists

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Ana Busic [Inria, Researcher]
Francesco Caltagirone [Inria, Starting Research Position, until Jan 2017]
Marc Lelarge [on leave at Safran in 2017, Researcher, HDR]

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Jocelyne Elias [Univ René Descartes, Associate Professor, by delegation, until Aug 2017]

Post-Doctoral Fellow

Arpan Mukhopadhyay [Inria, until Feb 2017]

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Lennart Gulikers [Inria, until Nov 2017]
Md Umar Hashmi [PSL]
Dalia-Georgiana Herculea [Bell Labs (Nokia)]
Alexandre Hollocou [Ministère de la Défense]
Quentin Le Gall [Orange, from Oct 2017]
Leo Miolane [Ecole polytechnique]

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Pierre Bremaud [Prof. Emeritus]
Marc Olivier Buob [Bell Labs (Alcatel)]
Josu Doncel [University of the Basque Country, Jul 2017]
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Christelle Rovetta [Univ Pierre et Marie Curie, from Jul 2017 until Aug 2017]

2. Overall Objectives

2.1. Overall Objectives

The general scientific focus of DYOGENE is on the development of network mathematics. The following theories lie within our research interest: dynamical systems, queuing theory, optimization and control, information theory, stochastic processes, random graphs, stochastic geometry.

Our theoretical developments are motivated by and applied in the context of communication networks (Internet, wireless, mobile, cellular, peer-to-peer), social and economic networks, power grids.

We collaborate with many industrial partners. Our current industrial relations involve EDF, Google, Huawei, Microsoft, Nokia, Orange, Safran.

More specifically, the scientific focus of DYOGENE defined in 2013 was 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 the one where the nodes or the links change 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 geometry and the local dynamics interplay. Our motivations for studying these systems stem from many fields of communications where they play a central role, and in particular: message passing algorithms; epidemic algorithms; wireless networks and information theory; device to device networking; distributed content delivery; social and economic networks, power grids.

3. Research Program

3.1. Initial research axes

The following research axes have been defined in 2013 when the project-team was created.

- Algorithms for network performance analysis, led by A. Bouillard and A. Busic.
- Stochastic geometry and information theory for wireless network, led by B. Blaszczyszyn and F. Baccelli.
- The cavity method for network algorithms, led by M. Lelarge.

Our scientific interests keep evolving. Research areas which received the most of our attention in 2017 are summarized in the following sections.

3.2. Distributed network control and smart-grids

Foundation of an entirely new science for distributed control of networks with applications to the stabilization of power grids subject to high volatility of renewable energy production is being developed A. Busic in collaboration with A. Bouillard and Sean Meyn [University of Florida].

3.3. Mathematics of wireless cellular networks

A comprehensive approach involving information theory, queueing and stochastic geometry to model and analyze the performance of large cellular networks, validated and implemented by Orange is being B. Blaszczyszyn in collaboration with F. Baccelli and M. K. Karray [Orange Labs]

3.4. High-dimensional statistical inference for social networks

Community detection and non-regular ramanujan graphs sole a conjecture on the optimality of non-backtracking spectral algorithm for community dectection in sparse stochastic block model graphs, as has been proved by M. Lelarge in collaboration with Ch. Bordenave [IMT Toulouse], L. Massoulié [MSR-Inria].

4. Application Domains

4.1. Physical communication networks

Internet, wireless, mobile, cellular networks.

4.2. Abstract networks

Social interactions, human communities, economic networks.

4.3. Power grids

Energy networks.

5. Highlights of the Year

5.1. Highlights of the Year

B. Blaszczyszyn has just been appointed ENS adjunct professor in September 2017.

6. New Software and Platforms

6.1. CloNES

CLOsed queueing Networks Exact Sampling
FUNCTIONAL DESCRIPTION: Clones is a Matlab toolbox for exact sampling of closed queueing networks.

- Participant: Christelle Rovetta
- Contact: Christelle Rovetta
- URL: http://www.di.ens.fr/~rovetta/Clones/index.html

6.2. Platforms

6.2.1. *CapRadio*

Cellular network dimensioning toolbox *CapRadio* is being developed by Orange in a long-term collaboration between TREC/DYOGENE represented by B. Blaszczyszyn, and Orange Labs, represented by M. K. Karray. This year it has been enriched by the results of the contract titled "Scheduling effect on the distribution of QoS over cells in 4G wireless cellular networks"; cf 8.1.1.

7. New Results

7.1. Reversibility and further properties of FCFS infinite bipartite matching

[3] The model of FCFS infinite bipartite matching was introduced in Caldentey, Kaplan, & Weiss Adv. Appl. Probab., 2009. In this model, there is a sequence of items that are chosen i.i.d. from a finite set C and an independent sequence of items that are chosen i.i.d. from a finite set S, and a bipartite compatibility graph G between C and S. Items of the two sequences are matched according to the compatibility graph, and the matching is FCFS, meaning that each item in the one sequence is matched to the earliest compatible unmatched item in the other sequence. In Adan & Weiss, Operations Research, 2012, a Markov chain associated with the matching was analyzed, a condition for stability was derived, and a product form stationary distribution was obtained. In the current paper, we present several new results that unveil the fundamental structure of the model. First, we provide a pathwise Loynes' type construction which enables to prove the existence of a unique matching for the model defined over all the integers. Second, we prove that the model is dynamically reversible: we define an exchange transformation in which we interchange the positions of each matched pair, and show that the items in the resulting permuted sequences are again independent and i.i.d., and the matching between them is FCFS in reversed time. Third, we obtain product form stationary distributions of several new Markov chains associated with the model. As a by product, we compute useful performance measures, for instance the link lengths between matched items.

7.2. Point-map-probabilities of a point process and Mecke's invariant measure equation

[4] A compatible point-shift F maps, in a translation invariant way, each point of a stationary point process Φ to some point of Φ. It is fully determined by its associated point-map, f, which gives the image of the origin by F. It was proved by J. Mecke that if F is bijective, then the Palm probability of Φ is left invariant by the translation of $-f$. The initial question motivating this paper is the following generalization of this invariance result: in the nonbijective case, what probability measures on the set of counting measures are left invariant by the translation of $-f$? The point-map-probabilities of Φ are defined from the action of the semigroup of point-map translations on the space of Palm probabilities, and more precisely from the compactification of the orbits of this semigroup action. If the point-map-probability exists, is uniquely defined and if it satisfies certain continuity properties, it then provides a solution to this invariant measure problem. Point-map-probabilities are objects of independent interest. They are shown to be a strict generalization of Palm probabilities: when F is bijective, the point-map-probability of Φ boils down to the Palm probability of Φ. When it is not bijective, there exist cases where the point-map-probability of Φ is singular with respect to its Palm probability. A tightness based criterion for the existence of the point-map-probabilities of a stationary point process is given. An interpretation of the point-map-probability as the conditional law of the point process given that the origin has F-pre-images of all orders is also provided. The results are illustrated by a few examples.

7.3. Gibbsian on-line distributed content caching strategy for cellular networks

[7] We develop Gibbs sampling based techniques for learning the optimal content placement in a cellular network. A collection of base stations are scattered on the space, each having a cell (possibly overlapping with other cells). Mobile users request for downloads from a finite set of contents according to some popularity distribution. Each base station can store only a strict subset of the contents at a time; if a requested content is not available at any serving base station, it has to be downloaded from the backhaul. Thus, there arises the problem of optimal content placement which can minimize the download rate from the backhaul, or equivalently maximize the cache hit rate. Using similar ideas as Gibbs sampling, we propose imple sequential content update rules that decide whether to store a content at a base station based on the knowledge of contents in neighbouring base stations. The update rule is shown to be asymptotically converging to the optimal content placement for all nodes. Next, we extend the algorithm to address the situation where content popularities and cell topology are initially unknown, but are estimated as new requests arrive to the base stations. Finally, improvement in cache hit rate is demonstrated numerically.

7.4. State estimation for the individual and the population in mean field control with application to demand dispatch

[10] This paper concerns state estimation problems in a mean field control setting. In a finite population model, the goal is to estimate the joint distribution of the population state and the state of a typical individual. The observation equations are a noisy measurement of the population. The general results are applied to demand dispatch for regulation of the power grid, based on randomized local control algorithms. In prior work by the authors it is shown that local control can be designed so that the aggregate of loads behaves as a controllable resource, with accuracy matching or exceeding traditional sources of frequency regulation. The operational cost is nearly zero in many cases. The information exchange between grid and load is minimal, but it is assumed in the overall control architecture that the aggregate power consumption of loads is available to the grid operator. It is shown that the Kalman filter can be constructed to reduce these communication requirements, and to provide the grid operator with accurate estimates of the mean and variance of quality of service (QoS) for an individual load.

7.5. Distributed spectrum management in TV white space networks

[11] In this paper, we investigate the spectrum management problem in TV White Space (TVWS) Cognitive Radio Networks using a game theoretical approach, accounting for adjacent-channel interference. TV Bands

Devices (TVBDs) compete to access available TV channels and choose idle blocks that optimize some objective function. Specifically, the goal of each TVBD is to minimize the price paid to the Database operator and a cost function that depends on the interference between unlicensed devices. We show that the proposed TVWS management game admits a potential function under general conditions. Accordingly, we use a Best Response algorithm to converge in few iterations to the Nash Equilibrium (NE) points. We evaluate the performance of the proposed game, considering both static and dynamic TVWS scenarios and taking into account users' mobility. Our results show that at the NE, the game provides an interesting tradeoff between efficient TV spectrum use and reduction of interference between TVBDs.

7.6. A spectral method for community detection in moderately sparse degree-corrected stochastic block models

[12] We consider community detection in degree-corrected stochastic block models. We propose a spectral clustering algorithm based on a suitably normalized adjacency matrix. We show that this algorithm consistently recovers the block membership of all but a vanishing fraction of nodes, in the regime where the lowest degree is of order log(n) or higher. Recovery succeeds even for very heterogeneous degree distributions. The algorithm does not rely on parameters as input. In particular, it does not need to know the number of communities.

7.7. Non-backtracking spectrum of degree-corrected stochastic block models

[25] Motivated by community detection, we characterise the spectrum of the non-backtracking matrix B in the Degree-Corrected Stochastic Block Model. Specifically, we consider a random graph on n vertices partitioned into two asymptotically equal-sized clusters. The vertices have i.i.d. weights $\{\phi_u\}_{u=1}^n$ with second moment $\Phi^{(2)}$. The intra-cluster connection probability for vertices u and v is $\frac{\phi_u \phi_v}{n} a$ and the inter-cluster connection probability is $\frac{\phi_u \phi_v}{n} b$. We show that with high probability, the following holds: The leading eigenvalue of the non-backtracking matrix B is asymptotic to $\rho = \frac{a+b}{2} \Phi^{(2)}$. The second eigenvalue is asymptotic to $\mu_2 = \frac{a-b}{2} \Phi^{(2)}$ when $\mu_2^2 > \rho$, but asymptotically bounded by $\sqrt{\rho}$ when $\mu_2^2 \leq \rho$. All the remaining eigenvalues are asymptotically bounded by $\sqrt{\rho}$. As a result, a clustering positively-correlated with the true communities can be obtained based on the second eigenvector of B in the regime where $\mu_2^2 > \rho$. In a previous work we obtained that detection is impossible when $\mu_2^2 < \rho$, meaning that there occurs a phase-transition in the sparse regime of the Degree-Corrected Stochastic Block Model. As a corollary, we obtain that Degree-Corrected Erdős-Rényi graphs asymptotically satisfy the graph Riemann hypothesis, a quasi-Ramanujan property. A by-product of our proof is a weak law of large numbers for local-functionals on Degree-Corrected Stochastic Block Models, which could be of independent interest.

7.8. A spectral algorithm with additive clustering for the recovery of overlapping communities in networks

[13] This paper presents a novel spectral algorithm with additive clustering designed to identify overlapping communities in networks. The algorithm is based on geometric properties of the spectrum of the expected adjacency matrix in a random graph model that we call stochastic blockmodel with overlap (SBMO). An adaptive version of the algorithm, that does not require the knowledge of the number of hidden communities, is proved to be consistent under the SBMO when the degrees in the graph are (slightly more than) logarithmic. The algorithm is shown to perform well on simulated data and on real-world graphs with known overlapping communities.

7.9. Optimal geographic caching in cellular networks with linear content coding

[14] We state and solve a problem of the optimal geographic caching of content in cellular networks, where linear combinations of contents are stored in the caches of base stations. We consider a general content

popularity distribution and a general distribution of the number of stations covering the typical location in the network. We are looking for a policy of content caching maximizing the probability of serving the typical content request from the caches of covering stations. The problem has a special form monotone sub-modular set function maximization. Using dynamic programming, we find a deterministic policy solving the problem. We also consider two natural greedy caching policies. We evaluate our policies considering two popular stochastic geometric coverage models: the Boolean one and the Signal-to-Interference-and-Noise-Ratio one, assuming Zipf popularity distribution. Our numerical results show that the proposed deterministic policies are in general not worst than some randomized policy considered in the literature and can further improve the total hit probability in the moderately high coverage regime.

7.10. Online mobile user speed estimation: performance and tradeoff considerations

[15] This paper presents an online algorithm for mobile user speed estimation in 3GPP Long Term Evolution (LTE)/LTE-Advanced (LTE-A) networks. The proposed method leverages on uplink (UL) sounding reference signal (SRS) power measurements performed at the base station, also known as eNodeB (eNB), and remains effective even under large sampling period. Extensive performance evaluation of the proposed algorithm is carried out using field traces from realistic environment. The on-line solution is proven highly efficient in terms of computational requirement, estimation delay, and accuracy. In particular, we show that the proposed algorithm can allow for the first speed estimation to be obtained after 10 seconds and with an average speed underestimation error of 14 kmph. After the first speed acquisition, subsequent speed estimations can be obtained much faster (e.g., each second) with limited implementation cost and still provide high accuracy.

7.11. Self-similarity in urban wireless networks: Hyperfractals

[18] In this work we study a Poisson patterns of fixed and mobile nodes distributed on straight lines designed for 2D urban wireless networks. The particularity of the model is that, in addition to capturing the irregularity and variability of the network topology, it exploits self-similarity, a characteristic of urban wireless networks. The pattern obeys to " Hyperfractal " measures which show scaling properties corresponding to an apparent dimension larger than 2. The hyperfractal pattern is best suitable for capturing the traffic over the streets and highways in a city. The scaling effect depends on the hyperfractal dimensions. Assuming radio propagation limited to streets, we prove results on the scaling of routing metrics and connectivity graph.

7.12. Optimizing spatial throughput in device-to-device networks

[19] Results are presented for optimizing device-to-device communications in cellular networks, while maintaining spectral efficiency of the base-station-to-device downlink channel. We build upon established and tested stochastic geometry models of signal-to-interference ratio in wireless networks based on the Poisson point process, which incorporate random propagation effects such as fading and shadowing. A key result is a simple formula, allowing one to optimize the device-to-device spatial throughput by suitably adjusting the proportion of active devices. These results can lead to further investigation as they can be immediately applied to more sophisticated models such as studying multi-tier network models to address coverage in closed access networks.

7.13. Demand dispatch with heterogeneous intelligent loads

[20] A distributed control architecture is presented that is intended to make a collection of heterogeneous loads appear to the grid operator as a nearly perfect battery. Local control is based on randomized decision rules advocated in prior research, and extended in this paper to any load with a discrete number of power states. Additional linear filtering at the load ensures that the input-output dynamics of the aggregate has a nearly flat input-output response: the behavior of an ideal, multi-GW battery system.

7.14. Energy savings for virtual MISO in fractal sensor networks

[21] We design a model of wireless terminals, i.e. transmitters and receivers, obtained from a Poisson point process with support in an embedded fractal map. The terminals form a virtual MISO (Multiple Input Single Output) system with successful reception under SNR (signal-to-noise ratio) capture condition in a single hop transmission. We show that if we omit antennas cross sections, the energy needed to broadcast a packet of information tends to zero when the density of transmitters and receivers increases. This property is a direct consequence of the fact that the support map is fractal and would not hold if the terminal distribution were Poisson uniform, as confirmed by simulations. The result becomes invalid if the cross sections overlap or if we consider a masking effect due to antennas, which would imply an extremely large density of terminals. In the case where the cross sections of the transmitters have a non-zero value, the energy has a non-zero limit which decays to zero when the cross sections tend to zero.

7.15. Distributed control of a fleet of batteries

[22] Battery storage is increasingly important for grid-level services such as frequency regulation, load following, and peak-shaving. The management of a large number of batteries presents a control challenge: How can we solve the apparently combinatorial problem of coordinating a large number of batteries with discrete, and possibly slow rates of charge/discharge? The control solution must respect battery constraints, and ensure that the aggregate power output tracks the desired grid-level signal. A distributed stochastic control architecture is introduced as a potential solution. Extending prior research on distributed control of flexible loads, a randomized decision rule is defined for each battery of the same type. The power mode at each time-slot is a randomized function of the grid-signal and its internal state. The randomized decision rule is designed to maximize idle time of each battery, and keep the state-of-charge near its optimal level, while ensuring that the aggregate power output can be continuously controlled by a grid operator or aggregator. Numerical results show excellent tracking, and low stress to individual batteries.

7.16. Exact Computation and bounds for the coupling time in queueing systems

[23] This paper is a work in progress on the exact computation and bounds of the expected coupling time for finite-state Markov chains. We give an exact formula in terms of generating series. We show how this may help to bound the expected coupling time for queueing networks.

7.17. An online disaggregation algorithm and its application to demand control

[24] The increase of renewable energy has made the supply-demand balance of power more complex to handle. Previous approach designed randomized controllers to obtain ancillary services to the power grid by harnessing inherent flexibility in many loads. However these controllers suppose that we know the consumption of each device that we want to control. This introduce the cost and the social constraint of putting sensors on each device of each house. Therefore, our approach was to use Nonintrusive Appliance Load Monitoring (NALM) methods to solve a disaggregation problem. The latter comes down to estimating the power consumption of each device given the total power consumption of the whole house. We started by looking at the Factorial Hierarchical Dirichlet Process-Hidden Semi-Markov Model (Factorial HDP-HSMM). In our application, the total power consumption is considered as the observations of this state-space model and the consumption of each device as the state variables. Each of the latter is modelled by an HDP-HSMM which is an extension of a Hidden Markov Model. However, the inference method proposed previously is based on Gibbs sampling and has a complexity of $O(T2N + TN2)$ where T is the number of observations and N is the number of hidden states. As our goal is to use the randomized controllers with our estimations, we wanted a method that does not scale with T. Therefore, we developed an online algorithm based on particle filters. Because we worked in a Bayesian setting, we had to infer the parameters of our model. To do so, we used a method called Particle Learning. The idea is to include the parameters in the state space so that they are tied to the particles. Then, for each (re)sampling step, the parameters are sampled from their posterior distribution with the help of Bayesian

sufficient statistics. We applied the method to data from Pecan Street. Using their Dataport, we have collected the power consumption of each device from about a hundred houses. We selected the few devices that consume the most and that are present in most houses. We separated the houses in a training set and a test set. For each device of each house from the training set, we estimated the operating modes with a HDP-HSMM and used these estimations to compute estimators of the priors hyperparameters. Finally we applied the particle filters method to the test houses using the computed priors. The algorithm performs well for the device with the highest power consumption, the air compressor in our case. We will discuss ongoing work where we apply the "Thermo-statically Controlled Loads" example using our estimations of this air compressor's operating modes.

7.18. Multiple local community detection

[26] Community detection is a classical problem in the field of graph mining. We are interested in local community detection where the objective is the recover the communities containing some given set of nodes, called the seed set. While existing approaches typically recover only one community around the seed set, most nodes belong to multiple communities in practice. In this paper, we introduce a new algorithm for detecting multiple local communities, possibly overlapping, by expanding the initial seed set. The new nodes are selected by some local clustering of the graph embedded in a vector space of low dimension. We validate our approach on real graphs, and show that it provides more information than existing algorithms to recover the complex graph structure that appears locally.

7.19. A Streaming Algorithm for Graph Clustering

[27] We introduce a novel algorithm to perform graph clustering in the edge streaming setting. In this model, the graph is presented as a sequence of edges that can be processed strictly once. Our streaming algorithm has an extremely low memory footprint as it stores only three integers per node and does not keep any edge in memory. We provide a theoretical justification of the design of the algorithm based on the modularity function, which is a usual metric to evaluate the quality of a graph partition. We perform experiments on massive real-life graphs ranging from one million to more than one billion edges and we show that this new algorithm runs more than ten times faster than existing algorithms and leads to similar or better detection scores on the largest graphs.

7.20. Discrete probability models and methods: probability on graphs and trees, markov chains and random fields, entropy and coding

[28] The emphasis in this book is placed on general models (Markov chains, random fields, random graphs), universal methods (the probabilistic method, the coupling method, the Stein-Chen method, martingale methods, the method of types) and versatile tools (Chernoff's bound, Hoeffding's inequality, Holley's inequality) whose domain of application extends far beyond the present text. Although the examples treated in the book relate to the possible applications, in the communication and computing sciences, in operations research and in physics, this book is in the first instance concerned with theory. The level of the book is that of a beginning graduate course. It is self-contained, the prerequisites consisting merely of basic calculus (series) and basic linear algebra (matrices). The reader is not assumed to be trained in probability since the first chapters give in considerable detail the background necessary to understand the rest of the book.

7.21. Distributed control design for balancing the grid using flexible loads

[29] nexpensive energy from the wind and the sun comes with unwanted volatility, such as ramps with the setting sun or a gust of wind. Controllable generators manage supply-demand balance of power today, but this is becoming increasingly costly with increasing penetration of renewable energy. It has been argued since the 1980s that consumers should be put in the loop: " demand response " will help to create needed supply-demand balance. However, consumers use power for a reason, and expect that the quality of service (QoS) they receive will lie within reasonable bounds. Moreover, the behavior of some consumers is unpredictable, while

the grid operator requires predictable controllable resources to maintain reliability. The goal of this chapter is to describe an emerging science for demand dispatch that will create virtual energy storage from flexible loads. By design, the grid-level services from flexible loads will be as controllable and predictable as a generator or fleet of batteries. Strict bounds on QoS will be maintained in all cases. The potential economic impact of these new resources is enormous. California plans to spend billions of dollars on batteries that will provide only a small fraction of the balancing services that can be obtained using demand dispatch. The potential impact on society is enormous: a sustainable energy future is possible with the right mix of infrastructure and control systems.

7.22. Un classificateur non-supervisé utilisant les complexes simpliciaux avec une application à la stylométrie

[30] Un classificateur non-supervisé utilisant les complexes simpliciaux (avec une application à la stylométrie). Nous nous proposons au cours des quelques pages de ce rapport de présenter au lecteur ce que sont les complexes simpliciaux ainsi qu'une de leurs possibles (et nombreuses !) applications : en classification non-supervisée. Les complexes simpliciaux peuvent s'appréhender comme une généralisation des graphes ; un graphe étant la donnée d'un ensemble de sommets ainsi que d'une relation de voisinage entre des paires de ces sommets (deux points sont voisins si une arête les relie). Les complexes simpliciaux permettent de rendre compte de relations de voisinage plus élaboré (et faisant notamment intervenir un nombre arbitraire de points ; pas seulement deux). La classification non supervisée est une branche du vaste domaine de l'apprentissage automatique. Etant donné un échantillon de données (le plus souvent des points de l'espace euclidien R^d), elle consiste a regrouper ces données en différentes classes de sorte que les données d'une même classe présentent des similarités entre elles tandis que deux données appartenant à deux classes distinctes soient dissemblables. Le présent rapport s'articulera donc en deux parties : la première introduira au lecteur non forcément familier cette notion de complexe simplicial d'un point de vue théorique. On l'illustrera ensuite avec la présentation des complexes de Cech et certaines propriétés mathématiques qui en font un outil puissant et pratique (la théorie de Morse permet, par exemple, de manier ces complexes de différentes façons). On verra encore quelques résultats des complexes simpliciaux aléatoires (c'est-à-dire que les sommets sont des points générés aléatoirement) dans le cas des régimes dits surcritiques jus-tifiant certains algorithmes d'apprentissage de variétés (une des multiples applications promises des complexes simpliciaux). Enfin, nous présenterons très succinctement l'homologie persistante...

7.23. Phase transitions, optimal errors and optimality of message-passing in generalized linear models

[31] We consider generalized linear models where an unknown nn-dimensional signal vector is observed through the successive application of a random matrix and a non-linear (possibly probabilistic) componentwise function. We consider the models in the high-dimensional limit, where the observation consists of $m \times n$ points, and $m/n \to \alpha$ where α stays finite in the limit $m, n \to \infty$. This situation is ubiquitous in applications ranging from supervised machine learning to signal processing. A substantial amount of work suggests that both the inference and learning tasks in these problems have sharp intrinsic limitations when the available data become too scarce or too noisy. Here, we provide rigorous asymptotic predictions for these thresholds through the proof of a simple expression for the mutual information between the observations and the signal. Thanks to this expression we also obtain as a consequence the optimal value of the generalization error in many statistical learning models of interest, such as the teacher-student binary perceptron, and introduce several new models with remarquable properties. We compute these thresholds (or "phase transitions") using ideas from statistical physics that are turned into rigorous methods thanks to a new powerful smart-path interpolation technique called the stochastic interpolation method, which has recently been introduced by two of the authors. Moreover we show that a polynomial-time algorithm refered to as generalized approximate message-passing reaches the optimal generalization performance for a large set of parameters in these problems. Our results clarify the difficulties and challenges one has to face when solving complex high-dimensional statistical problems.

7.24. Lecture notes on random geometric models — random graphs, point processes and stochastic geometry

[32] The goal of this sequence of lessons is to provide quick access to some popular models of random geometric structures used in many applications: from communication networks, including social, transportation, wireless networks, to geology, material sciences and astronomy. The course is composed of the following 15 lessons: (1) Bond percolation on the square lattice, (2) Galton-Watson tree, (3) Erdős-Rényi graph — emergence of the giant component, (4) Graphs with a given node degree distribution, (5) Typical nodes and random unimodular graphs, (6) Erdős-Rényi graph — emergence of the full connectivity, (7) Poisson point process, (8) Point conditioning and Palm theory for point processes, (9) Hard-core point processes, (10) Stationary point processes and mass transport principle, (11) Stationary Voronoi tessellation, (12) Ergodicity and point-shift invariance, (13) Random closed sets, (14) Boolean model and coverage processes, (15) Connectedness of random sets and continuum percolation. Usually, these subjects are presented in different monographs: random graphs (lessons 2–6), point processes (7-12), stochastic geometry (13-14), with percolation models presented in lesson 1 and 15 often addressed separately. Having them in one course gives us an opportunity to observe some similarities and even fundamental relations between different models. Examples of such connections are:

- Similar phase transitions regarding the emergence of big components observed in different discrete, lattice and continuous euclidean models (lessons 1–4, 15).

- Single isolated nodes being the last obstacle in the emergence of the full connectivity in some discrete and euclidean graphs exhibiting enough independence (lessons 6, 15).

- A mass transport principle as a fundamental property for unimodular random graphs and Palm theory for stationary point processes; with both theories seeking to define the typical node/point of a homogeneous structure (lessons 5, 10–12).

- Poisson-Galton-Watson tree and Poisson process playing a similar role in the theory of random graphs and point processes, respectively: for both models independence and Poisson distribution are the key assumptions, both appear as natural limits, and both rooted/conditioned to a typical node/point preserve the distribution of the remaining part of the structure (lessons 2,5, 7–8).

- Size biased sampling appearing in several, apparently different, conditioning scenarios, as unimodular trees (lesson 5), Palm distributions for point process (lesson 8), zero cell of the stationary tessellations (lessons 11).

The goal of this series of lectures is to present some spectrum of models and ideas. When doing this, we sometimes skip more technical proof details, sending the reader for them to more specialised monographs. Some theoretical and computer exercises are provided after each lesson to let the reader practice his/her skills. Regarding the prerequisites, the reader will benefit from having had some prior exposure to probability and measure theory, but this is not absolutely necessary.

The content of the course has been evolving while the author teaches it within the master programme *Probabilité et modelés aléatoires* at the University Pierre and Marie Curie in Paris. The present notes were thoroughly revised when the author was presenting them as a specially appointed professor at the School of Computing, Tokyo Institute of Technology, in the autumn term 2017.

7.25. Energy trade-offs for end-to-end communications in urban vehicular networks exploiting an hyperfractal model

[34] We present results on the trade-offs between the end-to-end communication delay and energy spent for completing a transmission in vehicular communications in urban settings. This study exploits our innovative model called "hyperfractal" that captures the self-similarity of the topology and vehicle locations in cities. We enrich the model by incorporating roadside infrastructure. We use analytical tools to derive theoretical bounds for the end-to-end communication hop count under two different energy constraints: either total accumulated energy, or maximum energy per node. More precisely, we prove that the hop count is bounded

by $O(n1-\alpha/(dm-1))$ where $\alpha < 1$ and d $m > 2$ is the precise hyperfractal dimension. This proves that for both constraints the energy decreases as we allow to chose among paths of larger length. In fact the asymptotic limit of the energy becomes significantly small when the number of nodes becomes asymptotically large. A lower bound on the network throughput capacity with constraints on path energy is also given. The results are confirmed through exhaustive simulations using different hyperfractal dimensions and path loss coefficients.

7.26. Fundamental limits of low-rank matrix estimation: the non-symmetric case

[36] We consider the high-dimensional inference problem where the signal is a low-rank symmetric matrix which is corrupted by an additive Gaussian noise. Given a probabilistic model for the low-rank matrix, we compute the limit in the large dimension setting for the mutual information between the signal and the observations, as well as the matrix minimum mean square error, while the rank of the signal remains constant. We also show that our model extends beyond the particular case of additive Gaussian noise and we prove an universality result connecting the community detection problem to our Gaussian framework. We unify and generalize a number of recent works on PCA, sparse PCA, submatrix localization or community detection by computing the information-theoretic limits for these problems in the high noise regime. In addition, we show that the posterior distribution of the signal given the observations is characterized by a parameter of the same dimension as the square of the rank of the signal (i.e. scalar in the case of rank one). Finally, we connect our work with the hard but detectable conjecture in statistical physics.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. CRE with Orange

One year contract titled "Scheduling effect on the distribution of QoS over cells in 4G wireless cellular networks" between Inria and Orange Labs have been realized in 2017. It is a part of the long-term collaboration between TREC/DYOGENE, represented by B. Blaszczyszyn and Orange Labs, represented by M. K. Karray, for the development of analytic tools for the QoS evaluation and dimensioning of operator cellular networks. The developed solutions are implemented in Orange dimensioning toolbox *CapRadio* 6.2.1. Antoine Brochard was hired by Inria as a research engineer thanks to this contract.

8.1.2. CRE with Huawei

18-month contract titled "Mathematical Modeling of 5G Ultra Dense Wireless Networks" between Inria represented by B. Blaszczyszyn (PI) and F. Baccelli, and Huawei. It aims at investigating obstacle-based shadowing fields in the spatial models of cellular networks and efficient scheduling policies. Paul Keeler was hired by Inria as a research engineer thanks to this contract.

8.1.3. Contract with the Ministry of Defense

The contract supports a PhD student Alexandre Hollocou hired in 2015, co-advised by M. Lelarge.

8.1.4. CIFRE with Nokia

Contract with Nokia started in 2015 for the co-advising by B. Blaszczyszyn of a PhD student of Nokia, Dalia-Georgiana Herculea.

8.1.5. CIFRE with Orange

Contract with Orange started in 2017 for the co-advising by B. Blaszczyszyn of a PhD student of Orange, Quentin Le Gall.

8.2. Bilateral Grants with Industry

8.2.1. Google Tides

Ana Busic and Sean Meyn received jointly in 2015 a Google Faculty Research Award for their research on Distributed Control for Renewable Integration in Smart Communities. The corresponding grant allowed us to cover some part of the scholarship of the PhD student **Sebastien Samain**. in 2017.

9. Partnerships and Cooperations

9.1. Regional Initiatives

DYOGENE is associated to the Laboratory of Information, Networking and Communication Sciences (LINCS) http://www.lincs.fr/ co-founded in 2010 by Inria, Institut Mines-Télécom and UPMC, with Bell Labs Nokia (formerly Alcatel-Lucent) and SystemX joining it as strategic partners in 2011 and 2014, respectively. The LINCS is dedicated to research and innovation in the domains of future information and communication networks, systems and services.

9.2. National Initiatives

9.2.1. GdR GeoSto

Members of Dyogene participate in Research Group GeoSto (Groupement de recherche, GdR 3477) http://gdr-geostoch.math.cnrs.fr/ on Stochastic Geometry led by Pierre Calka [Université de Rouen], Viet Chi Tran [Université de Lille] and David Coupier [Université de Valenciennes].

This is a collaboration framework for all French research teams working in the domain of spatial stochastic modeling, both on theory development and in applications.

9.2.2. GdR IM

Members of Dyogene participate in GdR-IM (Informatique-Mathématiques), https://www.gdr-im.fr/, working groups ALEA and SDA2 (Systèmes dynamiques, Automates et Algorithmique).

9.2.3. GdR RO

Members of Dyogene participate in GdR-RO (Recherche Opérationelle; GdR CNRS 3002), http://gdrro.lip6.fr/, working group COSMOS (Stochastic optimization and control, modeling and simulation), lead by A. Busic and E. Hyon (LIP 6); http://gdrro.lip6.fr/?q=node/78

9.2.4. PGMO

Gaspard Monge Program for Optimization and Operations Research project Decentralized control for renewable integration in smart-grids (2015-17). PI: A. Busic.

9.2.5. ANR MARMOTE

Markovian Modeling Tools and Environments - coordinator: Alain Jean-Marie (Inria Maestro); local coordinator (for partner Inria Paris-Rocquencourt): A. Bušić; Started: January 2013; Duration: 48 months; partners: Inria Paris-Rocquencourt (EPI DYOGENE), Inria Sophia Antipolis Méditerranée (EPI MAESTRO), Inria Grenoble Rhône-Alpes (EPI MESCAL), Université Versaillese-St Quentin, Telecom SudParis, Université Paris-Est Creteil, Université Pierre et Marie Curie.

The aim of the project was to realize a modeling environment dedicated to Markov models. One part developed the Perfect Simulation techniques, which allow one to sample from the stationary distribution of the process. A second one developed parallelization techniques for Monte Carlo simulation. A third one developed numerical computation techniques for a wide class of Markov models. All these developments were integrated into a programming environment allowing the specification of models and their solution strategy. Several applications have been studied in various scientific disciplines: physics, biology, economics, network engineering.

The project terminated in October 2017.

9.2.6. ANR JCJC PARI

Probabilistic Approach for Renewable Energy Integration: Virtual Storage from Flexible Loads. The project started in January 2017. PI — A. Bušić. This project is motivated by current and projected needs of a power grid with significant renewable energy integration. Renewable energy sources such as wind and solar have a high degree of unpredictability and time variation, which makes balancing demand and supply challenging. There is an increased need for ancillary services to smooth the volatility of renewable power. In the absence of large, expensive batteries, we may have to increase our inventory of responsive fossil-fuel generators, negating the environmental benefits of renewable energy. The proposed approach addresses this challenge by harnessing the inherent flexibility in demand of many types of loads. The objective of the project is to develop decentralized control for automated demand dispatch, that can be used by grid operators as ancillary service to regulate demand-supply balance at low cost. We call the resource obtained from these techniques virtual energy storage (VES). Our goal is to create the necessary ancillary services for the grid that are environmentally friendly, that have low cost and that do not impact the quality of service (QoS) for the consumers. Besides respecting the needs of the loads, the aim of the project is to design local control solutions that require minimal communications from the loads to the centralized entity. This is possible through a systems architecture that includes the following elements: i) local control at each load based on local measurements combined with a grid-level signal; ii) frequency decomposition of the regulation signal based on QoS and physical constraints for each class of loads.

9.3. International Initiatives

9.3.1. PARIS

> Title: Probabilistic Algorithms for Renewable Integration in Smart Grid

> International Partner (Institution - Laboratory - Researcher):

>> University of Florida (United States) - Laboratory for Cognition & Control in Complex Systems - Sean Meyn.

> Start year: 2015

> See also: http://www.di.ens.fr/~busic/PARIS/

> The importance of statistical modeling and probabilistic control techniques in the power systems area is now evident to practitioners in both the U.S. and Europe. Renewable generation has brought unforeseen volatility to the grid that require new techniques in distributed and probabilistic control. In a series of recent papers the two PIs have brought together their complementary skills in optimization, Markov modeling, simulation, and stochastic networks that may help to solve some pressing open problems in this area. This new research also opens many exciting new scientific questions.

9.3.2. Inria International Partners

9.3.2.1. Informal International Partners

- O. Mirsadeghi [Sharif University, Tehran],
- V. Anantharam [UC Berkeley],
- D. Yogeshwaran [Indian Statistical Institute].

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Venkat Anantharam [UC Berkeley, from Jun 2017 until Jul 2017]
- Prabir Barooah [University of Florida, from May 2017 until Jun 2017]

- Milan Bradonjic [Nokia, until Jan 2017]
- Adithya Munegowda Devraj [University of Florida, from Aug 2017 until Sep 2017]
- Christian Hirsch [LMU Munich, Sep 2017]
- Yuting Ji [Stanford, Oct 2017]
- Marc Olivier Buob [Bell Labs (Alcatel)]
- Josu Doncel [University of the Basque Country, Jul 2017]
- Mir Omid Haji Mirsadeghi [Sharif University, Tehran]

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

- B. Blaszczyszyn, October 1st – December 15th, Specially Appointed Professor at The School of Computing, Tokyo Institute of Technology.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Conference Program Committees

- Ana Busic: QEST 2017.

10.1.1.2. Reviewer

All members of the team act as reviewers for numerous conferences.

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

François Baccelli: Bernoulli, Queueing Systems.

10.1.2.2. Reviewer - Reviewing Activities

All members of the team act as reviewers for numerous scientific journals.

10.1.3. Invited Talks

- François Baccelli
  - WiOpt, Paris, May 2017, keynote speaker,
  - WITMSE, Paris, September 2017; plenary speaker.
  - 2nd Symposium on Spatial Networks, Oxford, September 2017; invited talk.
- Bartek Blaszczyszyn
  - LINCS Scientific Committee Workshop, Paris, June 2017; invited talk.
  - Tokyo Institute of Technology, November 2017; invited talk.
  - Kyushu Unuversuty, November 2017, invited talk.
- Ana Busic
  - Tutorial speaker at YEQT XI: "Winterschool on Energy Systems", December, 2017; https://www.eurandom.tue.nl/event/yeqt-xi-winter-school-on-energy-systems/
  - Inviter speaker at Second Conference on the Mathematics of Energy Markets Wolfgang Pauli Institute, Vienna, July, 2017; https://www.mn.uio.no/math/english/research/groups/store/events/conferences/second-conference-on-the-mathematics-of-energy-mar.html
  - Inviter speaker at PDE and Probability Methods for Interactions, Sophia Antipolis (France), March 2017; https://project.inria.fr/pde2017/

10.1.4. Leadership within the Scientific Community

Since 2014: A. Busic is leading (with E. Hyon, Univ. Paris Ouest Nanterre et LIP6) the working group GdT COSMOS (Stochastic Control and Optimization, Modeling, and Simulation) of CNRS research network GdR RO; http://gdrro.lip6.fr/?q=node/78. This includes scientific organization of 2 one-day workshops per year (30-50 participants).

10.1.5. Research Administration

A. Busic : Member of the Conseil du DI ENS.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: A. Busic (Cours) and Sébastien Samain (TD) **Structures et algorithmes aléatoires** 80heqTD, L3, ENS, France.

Licence: B. Blaszczyszyn (Cours) **Théorie de l'information et du codage** 24 heqTD, L3, ENS, France.

Master: A. Busic (Cours + TD) **Fondements de la modélisation des réseaux** 18 heqTD, L3, ENS, France.

Master: Bartlomiej Blaszczyszyn (Cours) **Processus ponctuels, graphes aléatoires et géeométrie stochastique** 39heqTD, M2 Probabilités et Modèles Aléatoires, UPMC, France

Master: Ana Busic and Marc Lelarge (Cours) et Rémi Varloot (TD) **Modéles et algorithmes de réseaux**, 50 heqTD, M1, ENS, Paris, France.

Master: B. Blaszczyszyn **Introduction to Spatial Stochastic Modeling: Random Graphs, Point Processes and Stochastic Geometry** (School of Computing, Tokyo Institute of Technology), 15 lessons 1h30.

10.2.2. Supervision

PhD: Lennart Gulikers "Trouver des algorithmes permettant de détecter des communautés dans des réseaux sociaux. Analyse de *Stochastic Block Model* et ses extensions" since 2015, defense 13 November 2017, going to Safran, supervised by Marc Lelarge with Laurent Massoulié.

PhD: Christelle Rovetta "Applications of perfect sampling to queuing networks and random generation of combinatorial objects", since December 2013, defense 20 June 2017, co-advised by Anne Bouillard and Ana Busic.

PhD in progress: Léeo Miolane, since 2016, supervised by Marc Lelarge

PhD in progress: Dalia-Georgiana Herculea, since October 2016 co-advised by B. Blaszczyszyn, E. Altman and Ph. Jacquet

PhD in progress: Md Umar Hashmi, Decentralized control for renewable integration in smartgrids, from December 2015, co-advised by A. Busic and M. Lelarge

PhD in progress: Alexandre Hollocou, since December 2015, supervised by Marc Lelarge with Thomas Bonald

PhD in progress: Sébastien Samain, Monte Carlo methods for performance evaluation and reinforcement learning, from November 2016, supervised by A. Busic

PhD in progress: Quentin Le Gall, since October 2017, co-supervised by B. Blaszczyszyn and E. Cali (Orange).

PhD in progress: Arnaud Cadas [PSL] "Dynamic matching models", since 2017, supervised by A. Busic.

10.2.3. Juries

- B. Blaszczyszyn, PhD defense of Frederik Mallmann-Trenn (ENS).
- A. Busic
  - Co-president of the Commission Emplois Scientifiques (CES) at Inria Paris (hiring committee for PhD, post-doc and visiting professor positions);

– Member of the hiring committee for Assistant Professor at Ecole Normale Supérieure and IUT Orsay.

11. Bibliography

Major publications by the team in recent years

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[2] F. BACCELLI, B. BŁASZCZYSZYN. *Stochastic Geometry and Wireless Networks, Volume II — Applications*, Foundations and Trends in Networking, Now Publishers, 2009, vol. 4, No 1–2, pp. 1–312

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