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ACTIVITY REPORT

Project-Team DYOGENE

Dynamics of Geometric Networks

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

DOMAIN

Networks, Systems and Services, Distributed Computing

THEME

Networks and Telecommunications

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Project-Team DYOGENE

Creation of the Project-Team: 2013 July 01

Keywords

Computer sciences and digital sciences

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

Other research topics and application domains

B4.3. – Renewable energy production

B6.2.2. – Radio technology

B6.3.4. – Social Networks

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2 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, and, recently, infectious diseases.

We collaborate with many industrial partners. Our current industrial relations involve EDF, 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, neural networks, and power grids.

3 Research program

Here are our main research accesses.

- Distributed network control and smart-grids 5.1
- Stochastic matching and queueing systems 5.2
- Reinforcement learning 5.3
- Mathematics of wireless cellular networks 5.4
- High-dimensional statistical inference and distributed learning 5.5
- Distributed optimization for machine learning 5.6
- Random Geometry 5.7
- Mathematics of stochastic networks via mean-field analysis 5.8

4 Application domains

4.1 Physical communication networks

Internet, wireless, mobile, cellular networks, transportation networks, distributed systems (cloud, call centers). In collaboration with Nokia Bell Labs and Orange Labs.

4.2 Abstract networks

Social interactions, human communities, economic networks.

4.3 Power grids

Energy networks. In collaboration with EDF and Vito (Belgium).

5 New results

Participants: All Dyogene.

5.1 Distributed network control and smart-grids

1. ***A unified framework for coordination of thermostatically controlled loads*** [4] A collection of thermostatically controlled loads (TCLs) – such as air conditioners and water heaters – can vary their power consumption within limits to help the balancing authority of a power grid maintain demand supply balance. Doing so requires loads to coordinate their on/off decisions so that the aggregate power consumption profile tracks a grid-supplied reference. At the same time, each consumer's quality of service (QoS) must be maintained. While there is a large body of work on TCL coordination, there are several limitations. One is that they do not provide guarantees on the reference tracking performance and QoS maintenance. A second limitation of past work is that they do not provide a means to compute a suitable reference signal for power demand of a collection of TCLs. In this work we provide a framework that addresses these weaknesses. The framework enables coordination of an arbitrary number of TCLs that: (i) is computationally efficient, (ii) is implementable at the TCLs with local feedback and low communication, and (iii) enables reference tracking by the collection while ensuring that temperature and cycling constraints are satisfied at every TCL at all times. The framework is based on a Markov model obtained by discretizing a pair of Fokker-Planck equations derived in earlier work by Malhame and Chong [21]. We then use this model to design randomized policies for TCLs. The balancing authority broadcasts the same policy to all TCLs, and each TCL implements this policy which requires only local measurement to make on/off decisions. Simulation results are provided to support these claims.

2. ***Load-Level Control Design for Demand Dispatch With Heterogeneous Flexible Loads*** [8]Over the past decade, there has been significant progress on the science of load control for the creation of virtual energy storage. This is an alternative to demand response, and it is termed demand dispatch. Distributed control is used to manage millions of flexible loads to modify the power consumption of the aggregation, which can be ramped up and down, just like discharging and charging a battery. A challenge with distributed control is heterogeneity of the population of loads, which complicates control at the aggregate level. It is shown in this article that additional control at each load in the population can result in a far aggregate model. The local control is designed to flatten resonances and produce approximately all-pass response. Analysis is based on mean-field control for the heterogeneous population; the mean-field model is only justified because of the additional local control introduced in this article. Theory and simulations indicate that the resulting input–output dynamics of the aggregate has a nearly flat input–output response: the behavior of an ideal, multi-GW battery system.

3. *Game-Theoretic Approaches for Peer-to-Peer Energy Trading* [25] Electricity markets are increasingly being decentralized, integrating more Distributed Energy Resources (DERs) and consumer-focused models. This transition presents new challenges and requires updated market models. This thesis explores these complexities, focusing on the coordination of diverse players, demand-supply management, distribution constraints, and information asymmetry. It utilizes game-theoretic approaches, examining frameworks for peer-to-peer electricity markets with risk-averse agents and prosumers hedging risks through financial contracts. It also investigates the interplay between physical and financial levels, comparison of centralized and fully distributed market designs, and addresses the issue of information asymmetry. Lastly, it explores coupling forecast markets with the electricity market. The findings emphasize the importance of additional services and information exchange in these strategic environments.

4. *A Stackelberg Game Analysis of Risk-Hedging Strategies in Decentralized Electricity Markets* [35] We investigate equilibrium problems arising in various decentralized designs of the electricity market involving riskaverse prosumers. The prosumers have the possibility to hedge their risks through financial contracts that they can trade with peers or purchase from an insurance company. We build several market designs of increasing complexity, from a one-stage market design with inter-agent financial contract trading to a Stackelberg game where an insurance company acts as a leader and prosumers are followers. We derive risk-hedging pricing scheme for each model and show that the Stackelberg game pessimistic formulation might have no solution. We propose an equivalent reformulation as a parametrizated generalized Nash equilibrium problem, and characterize the set of equilibria. We prove that the insurance company can design price incentives that guarantee the existence of a solution of the pessimistic formulation, which is ε close to the optimistic one. We then derive economic properties of the Stackelberg equilibria such as fairness, equity, and efficiency. We also quantify the impact of the insurance company incomplete information on the prosumers' riskaversion levels on its cost and social cost. Finally, we evaluate numerically the proposed risk-hedging market models, using residential data provided by Pecan Street.

5.2 Stochastic matching and queueing systems

5. *Stochastic Matching Model with Returning Items* [11] We consider a stochastic matching model with general compatibility graph and returning items. The return time is modeled by the sojourn time in a Jackson network. After being matched at their arrival, the items move to a Jackson network where they spend some time before eventually returning to the matching system. This general setting includes phase-type return times as a special case. We prove that under some assumptions about the routing and service in the Jackson network, the steady-state distribution of the Markov chain has a product form solution.

6. *On the sub-additivity of stochastic matching* [34] We consider a stochastic matching model with a general compatibility graph, as introduced by Mairesse and Moyal in 2016. We prove that most common matching policies (including FCFM, priorities and random) satisfy a particular sub-additive property, which we exploit to show in many cases, the coupling-from-the-past to the steady state, using a backwards scheme *à la* Loynes. We then use these results to explicitly construct perfect bi-infinite matchings, and to build a perfect simulation algorithm in the case where the buffer of the system is finite.

7. *Performance Paradox of Dynamic Matching Models under Greedy Policies* [26]We consider the stochastic matching model on a non-bipartite matching graph and analyze the impact of adding an edge to the expected number of items in the system. One may see adding an edge as increasing the flexibility of the system, for example asking a family registering for social housing to list less requirements in order to be compatible with more housing units. Therefore it may be natural to think that adding edges to the matching graph will lead to a decrease of the expected number of items in the system and the waiting time to be matched. In our previous work, and we proved this is not always true for the First Come First Matched discipline and provided sufficient conditions for the existence of the performance paradox: despite a new edge in the matching graph, the expected total number of items can increase. These sufficient conditions are related to the heavy-traffic assumptions in queueing systems. The intuition behind is that the performance paradox occurs when the added edge in the compatibility graph disrupts the draining of a bottleneck. In this paper, we generalize this performance paradox result to a family of so called greedy matching policies and explore the type of matching graphs where such paradoxes occur. Intuitively, a greedy matching policy never leaves compatible items unmatched, so the state space of the system consists of finite words of item classes that belong to an independent set of the matching graph. Some examples of greedy Performance Paradox of Dynamic Matching Models under Greedy Policies matching policies are First Come First Match, Match the Longest, Match the Shortest, Random selection, Priority. We prove several results about the existence of performance paradoxes for greedy disciplines for some family of graphs. More precisely, we prove several results about the lifting of the paradox from one graph to another one. For a certain family of graphs we prove that there exists a paradox for the whole family of greedy policies. Most of these results are based on Strong Aggregation of Markov chains and graph theoretical properties.

8. ***Stochastic dynamic matching: A mixed graph-theory and linear-algebra approach*** [28] The stochastic dynamic matching problem has recently drawn attention in the stochastic-modeling community due to its numerous applications, ranging from supply-chain management to kidney exchange programs. In this paper, we consider a matching problem in which items of different classes arrive according to independent Poisson processes. Unmatched items are stored in a queue, and compatibility constraints are described by a simple graph on the classes, so that two items can be matched if their classes are neighbors in the graph. We analyze the efficiency of matching policies, not only in terms of system stability, but also in terms of matching rates between different classes. Our results rely on the observation that, under any stable policy, the matching rates satisfy a conservation equation that equates the arrival and departure rates of each item class. Our main contributions are threefold. We first introduce a mapping between the dimension of the solution set of this conservation equation, the structure of the compatibility graph, and the existence of a stable policy. In particular, this allows us to derive a necessary and sufficient stability condition that is verifiable in polynomial time. Secondly, we describe the convex polytope of non-negative solutions of the conservation equation. When this polytope is reduced to a single point, we give a closed-form expression of the solution; in general, we characterize the vertices of this polytope using again the graph structure. Lastly, we show that greedy policies cannot, in general, achieve every point in the polytope. In contrast, non-greedy policies can reach any point of the interior of this polytope, and we give a condition for these policies to also reach the boundary of the polytope.

5.3 Reinforcement learning

9. ***Inverse Free Zap Stochastic Approximation Extended Abstract*** [17] The Zap Zero algorithm is introduced, a stochastic approximation algorithm designed to approximate the Newton-Raphson flow. It is stable and convergent under under the same assumptions required for Zap stochastic approximation, which achieves the same approximation. The significant advantage of the new algorithm is that matrix inversion is avoided. To estimate a parameter of dimension d, the Zap Zero algorithm requires parameter updates of dimension $3 \times$ d.Motivation and stability analysis is based on the ODE method and the theory of two time-scale stochastic approximation. The ODE itself can be interpreted as the solution to a particular linear quadratic regulator problem, even though the algorithm is designed for nonlinear root finding problems.

10. ***Learning Optimal Policies in Mean Field Models with Kullback-Leibler Regularization*** [12] The theory and application of mean field games has grown significantly since its origins less than two decades ago. This paper considers a special class in which the game is cooperative, and the cost includes a control penalty defined by Kullback-Leibler divergence, as commonly used in reinforcement learning and other fields. Its use as a control cost or regularizer is often preferred because this leads to an attractive solution. This paper considers a particular control paradigm called Kullback-Leibler Quadratic (KLQ) optimal control, and arrives at the following conclusions: 1. in application to distributed control of electric loads, a new modeling technique is introduced to obtain a simple Markov model for each load (the 'agent' in mean field theory). 2. It is argued that the optimality equations may be solved using Monte-Carlo techniques—a specialized version of stochastic gradient descent (SGD). 3. The use of averaging minimizes the asymptotic covariance in the SGD algorithm; the form of the optimal covariance is identified for the first time.

11. ***Kullback–Leibler-Quadratic Optimal Control*** [2] This paper presents approaches to mean-field control, motivated by distributed control of multiagent systems. Control solutions are based on a convex optimization problem, whose domain is a convex set of probability mass functions (pmfs). The main contributions follow: (1) Kullback–Leibler-quadratic (KLQ) optimal control is a special case in which the objective function is composed of a control cost in the form of Kullback–Leibler divergence between a candidate pmf and the nominal, plus a quadratic cost on the sequence of marginals. Theory in this paper extends prior work on deterministic control systems, establishing that the optimal solution is an exponential tilting of the nominal pmf. Transform techniques are introduced to reduce complexity of the KLQ solution, motivated by the need to consider time horizons that are much longer than the intersampling times required for reliable control. (2) Infinite-horizon KLQ leads to a state feedback control solution with attractive properties. It can be expressed as state feedback, in which the state is the sequence of marginal pmfs, or an open loop solution is obtained that is more easily computed. (3) Numerical experiments are surveyed in an application of distributed control of residential loads to provide grid services, similar to utility-scale battery storage. The results show that KLQ optimal control enables the aggregate power consumption of a collection of flexible loads to track a time-varying reference signal, while simultaneously ensuring each individual load satisfies its own quality of service constraints.

12. ***Reinforcement Learning Based Demand Charge Minimization Using Energy Storage*** [19]Utilities have introduced demand charges to en-courage customers to reduce their demand peaks, since a high peak may cause very high costs for both the utility and the consumer. We herein study the bill minimization problem for customers equipped with an energy storage device and a self-owned renewable energy production. A model-free reinforcement learning algorithm is carefully designed to reduce both the energy charge and the demand charge of the consumer. The proposed algorithm does not need forecasting models for the energy demand and the renewable energy production. The resulting controller can be used online, and progressively improved with newly gathered data. The algorithm is validated on real data from an office building of IFPEN Solaize site. Numerical results show that our algorithm can reduce electricity bills with both daily and monthly demand charges.

13. ***FLEX: an Adaptive Exploration Algorithm for Nonlinear Systems*** [10]Model-based reinforcement learning is a powerful tool, but collecting data to fit an accurate model of the system can be costly. Exploring an unknown environment in a sample-efficient manner is hence of great importance. However, the complexity of dynamics and the computational limitations of real systems make this task challenging. In this work, we introduce FLEX, an exploration algorithm for nonlinear dynamics based on optimal experimental design. Our policy maximizes the information of the next step and results in an adaptive exploration algorithm, compatible with generic parametric learning models and requiring minimal resources. We test our method on a number of nonlinear environments covering different settings, including time-varying dynamics. Keeping in mind that exploration is intended to serve an exploitation objective, we also test our algorithm on downstream model-based classical control tasks and compare it to other state-of-theart model-based and model-free approaches. The performance achieved by FLEX is competitive and its computational cost is low.

14. ***Brief Announcement: Efficient Collaborative Tree Exploration with Breadth-First Depth-Next*** [14]

5.4 Mathematics of wireless cellular networks

15. ***Extending the LOS Coverage of Vehicular Networks Based on Roadside Units and Vehicle Relays*** [13]This paper investigates the benefits of employing vehicle relays by analyzing the increment of the line-of-sight (LOS) coverage based on vehicle relays to enable high-speed communications between roadside user devices, vehicles, and roadside infrastructure. We characterize a unique spatial relationship between roadside units (RSUs) and vehicles by employing the Cox point processes. Then, the LOS coverage from these RSUs is modeled by a Boolean model on the Cox point process. Assuming vehicle relays provide an additional LOS coverage when they are within the RSU LOS coverage, we quantify the growth of the LOS coverage by separately deriving the mean area fractions of the RSU LOS coverage and RSU-plus-relay LOS coverage, respectively. We explicitly provide the gain in the LOS coverage as an integral formula and show that relays increase the LOS coverage area by nearly 50 percent.

16. ***LOS Coverage Area in Vehicular Networks with Cox-Distributed Roadside Units and Relays*** [3]We develop an analytical framework to examine the line-of-sight (LOS) coverage area in vehicular networks with roadside units (RSU) and vehicle relays. In practical deployment scenarios, RSUs and vehicle relays are spatially correlated and we characterize this by employing Cox point processes to model the locations of RSUs and vehicle relays simultaneously. Leveraging the random blockage model, we model the LOS coverage area as Boolean models on these Cox point processes. The LOS coverage area is then evaluated by its area fraction. We show that relays can increase the area fraction of LOS coverage by nearly 50% even when RSUs and relays are spatially correlated. By presenting a stochastic geometry model for a vehicular network with RSUs and relays and then by providing a tool to capture its LOS coverage, our work assesses the viability of vehicle relays for modern vehicular networks exploiting LOS coverage.

17. ***Spatial Network Calculus and Performance Guarantees in Wireless Networks*** [6] This work develops a novel approach toward performance guarantees for all links in arbitrarily large wireless networks. It introduces a spatial network calculus, consisting of spatial regulation properties for stationary point processes and the first steps of a calculus for this regulation, which can be seen as an extension to space of the classical network calculus. Specifically, two classes of regulations are defined: one includes ball regulation and shot-noise regulation, which are shown to be equivalent and upper constraint interference; the other one includes void regulation, which lower constraints the signal power. These regulations are defined both in the strong and weak sense: the former requires the regulations to hold everywhere in space, whereas the latter only requires the regulations to hold as observed by a jointly stationary point process. Using this approach, we derive performance guarantees in device-to-device, ad hoc, and cellular networks under proper regulations. We give universal bounds on the SINR for all links, which gives link service guarantees based on information-theoretic achievability. They are combined with classical network calculus to provide end-to-end latency guarantees for all packets in wireless queuing networks. Such guarantees do not exist in networks that are not spatially regulated, e.g., Poisson networks.

18. ***Connectivity and interference in device-to-device networks in Poisson-Voronoi cities*** [16] To study the overall connectivity in device-to-device networks in cities, we incorporate a signal-to-interference-plus-noise connectivity model into a Poisson-Voronoi tessellation model representing the streets of a city. Relays are located at crossroads (or street intersections), whereas (user) devices are scattered along streets. Between any two adjacent relays, we assume data can be transmitted either directly between the relays or through users, given they share a common street. Our simulation results reveal that the network connectivity is ensured when the density of users (on the streets) exceeds a certain critical value. But then the network connectivity disappears when the user density exceeds a second critical value. The intuition is that for longer streets, where direct relay-to-relay communication is not possible, users are needed to transmit data between relays, but with too many users the interference becomes too strong, eventually reducing the overall network connectivity. This observation on the user density evokes previous results based on another wireless network model, where transmitter-receivers were scattered across the plane. This effect disappears when interference is removed from the model, giving a variation of the classic Gilbert model and recalling the lesson that neglecting interference in such network models can give overly optimistic results. For physically reasonable model parameters, we show that crowded streets (with more than six users on a typical street) lead to a sudden drop in connectivity. We also give numerical results outlining a relationship between the user density and the strength of any interference reduction techniques.

19. ***Energy and Delay Trade-Offs of End-to-End Vehicular Communications using a Hyperfractal Urban Modelling*** [1] We characterize trade-offs between the end-to-end communication delay and the energy in urban vehicular communications with infrastructure assistance. Our study exploits the self-similarity of the location of communication entities in cities by modeling them with a hyperfractal model which charaterizes the distribution of mobile nodes and relay nodes by a fractal dimension d_F and d_r, both larger than the dimension of the embedded map. We compute theoretical bounds for the end-to-end communication hop count considering two different energy-minimizing goals: either total accumulated energy or maximum energy per node. Let $\delta > 1$ be the attenuation factor in the street, we prove that when we aim to a total energy cost of order $n^{(1-\delta)(1-\alpha)}$ the hop count for an end-to-end transmission is of order $n^{1-\alpha/(d_F-1)}$, with $\alpha < 1$ is a tunable parameter. This proves that for both goals the energy decreases as we allow choosing routing paths of higher length. 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. We show that our model fits real deployments where open data sets are available.

20. ***Study of the dynamics of spatial point processes in wireless communication networks*** [23]Thanks to the new paradigms introduced in the latest generation of wireless networks, expectations concerning service time, latency and network performance have increased. To model such networks, point process theory and stochastic geometry have proven to be useful as they provide a versatile and robust framework to obtain results when working with such wireless networks. Adding to this Markov dynamics to model connections and service times completes this framework to analyze such wireless networks. The first contribution of the work presented in this thesis lies in the analysis of service differentiation: 5G NR networks have introduced bandwidth partitioning as a tool to increase network performance. Under this network setup, not all users interfere with each other with the same power: users transmitting with a broader transmitting frequency spectrum will have a larger bandwidth, but they will also encounter more interference from the other users in the network. In contrast, users with a narrower spectrum will experience less interference. We define a Markovian framework to study such a multiclass spatial birth-and-death process, and we describe its stability re- gion. For such systems, properties of the stationary regime are analyzed, such as moment measures or statistical clustering, leading to a better understanding of these dynamics. The second problem we look into is mobility, which has become an important feature in wireless networks due to the use of highly directional antennas. Using a simple architecture for a two-tier cellular network, we study two families of association policies: a first family which only relies on user mobility, and the second offers a trade-off between network geometry and user mobility to increase network performance. These policies are then compared to a classical max-power association policy to assert their performance.

21. ***Energy and Delay Trade-Offs of End-to-End Vehicular Communications using a Hyperfractal Urban Modelling*** [1] We characterize trade-offs between the end-to-end communication delay and the energy in urban vehicular communications with infrastructure assistance. Our study exploits the self-similarity of the location of communication entities in cities by modeling them with an innovative model called "hyperfractal". We show that the hyperfractal model can be extended to incorporate road-side infrastructure and provide stochastic geometry tools to allow a rigorous analysis. We compute theoretical bounds for the end-to-end communication hop count considering two different energy-minimizing goals: either total accumulated energy or maximum energy per node. We prove that the hop count for an end-to-end transmission is bounded by $O(n^{1-\alpha/(d_F-1)})$ where $\alpha < 1$ and $d_F > 2$ is the fractal dimension of the mobile nodes process. This proves that for both constraints the energy decreases as we allow choosing routing paths of higher length. 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. We show that our model fits real deployments where open data sets are available. The results are confirmed through simulations using different fractal dimensions in a Matlab simulator.

5.5 High-dimensional statistical inference and distributed learning

22. ***Asymmetric tree correlation testing for graph alignment*** [18]We consider the partial graph alignment problem on two correlated sparse Erdős-Rényi graphs with differing edge or node densities. Exploiting that these graphs are locally tree-like, we come to consider a hypothesis testing problem on correlated Galton-Watson trees. To solve this problem, we give several equivalent conditions for the existence of likelihood-ratio tests with vanishing type-I-error and significant power. We then show that these same conditions enable the partial graph alignment algorithm MPAlign to succeed. This paper generalizes recent results from Ganassali L., Massoulié L. and Lelarge M. to the asymmetric edge and node density case. This extension allows for greater applicability of the results and resolves a special case of the subgraph isomorphism problem.

23. ***Statistical limits of correlation detection in trees*** [31] In this paper we address the problem of testing whether two observed trees (t, t') are sampled either independently or from a joint distribution under which they are correlated. This problem, which we refer to as correlation detection in trees, plays a key role in the study of graph alignment for two correlated random graphs. Motivated by graph alignment, we investigate the conditions of existence of one-sided tests, i.e. tests which have vanishing type I error and non-vanishing power in the limit of large tree depth. For the correlated Galton-Watson model with Poisson offspring of mean $\lambda > 0$ and correlation parameter $s \in (0,1)$, we identify a phase transition in the limit of large degrees at $s = \sqrt{\alpha}$, where $\alpha \sim 0.3383$ is Otter's constant. Namely, we prove that no such test exists for $s \leq \sqrt{\alpha}$, and that such a test exists whenever $s > \sqrt{\alpha}$, for λ large enough. This result sheds new light on the graph alignment problem in the sparse regime (with $O(1)$ average node degrees) and on the performance of the MPAlign method studied in Ganassali et al. (2021), Piccioli et al. (2021), proving in particular the conjecture of Piccioli et al. (2021) that MPAlign succeeds in the partial recovery task for correlation parameter $s > \sqrt{\alpha}$ provided the average node degree λ is large enough.

5.6 Distributed optimization for machine learning

24. ***(S)GD over Diagonal Linear Networks: Implicit Regularisation, Large Stepsizes and Edge of Stability*** [5] In this paper, we investigate the impact of stochasticity and large stepsizes on the implicit regularisation of gradient descent (GD) and stochastic gradient descent (SGD) over diagonal linear networks. We prove the convergence of GD and SGD with macroscopic stepsizes in an overparametrised regression setting and characterise their solutions through an implicit regularisation problem. Our crisp characterisation leads to qualitative insights about the impact of stochasticity and stepsizes on the recovered solution. Specifically, we show that large stepsizes consistently benefit SGD for sparse regression problems, while they can hinder the recovery of sparse solutions for GD. These effects are magnified for stepsizes in a tight window just below the divergence threshold, in the "edge of stability" regime. Our findings are supported by experimental results.

25. ***Efficient Collaborative Tree Exploration with Breadth-First Depth-Next*** [15] We consider the problem of *collaborative tree exploration* posed by Fraigniaud, Gasieniec, Kowalski, and Pelc in 2006 where a team of k agents is tasked to collectively go through all the edges of an unknown tree as fast as possible. Denoting by n the total number of nodes and by D the tree depth, the $\mathcal{O}(n/\log(k)+D)$ algorithm of Fraigniaud, Gasieniec, Kowalski, and Pelc achieves the best-known competitive ratio with respect to the cost of offline exploration which is $\Theta(\max\{2n/k, 2D\})$. Brass, Cabrera-Mora, Gasparri, and Xiao in 2011 consider an alternative performance criterion, namely the additive overhead with respect to $2n/k$, and obtain a $2n/k+\mathcal{O}((D+k)^k)$ runtime guarantee. In this paper, we introduce 'Breadth-First Depth-Next' (BFDN), a novel and simple algorithm that performs collaborative tree exploration in time $2n/k+\mathcal{O}(D^2\log(k))$, thus outperforming Brass et al. for all values of (n,D) and being order-optimal for all trees with depth $D = o_k(\sqrt{n})$. Moreover, a recent result from Disser et al. implies that no exploration algorithm can achieve a $2n/k+\mathcal{O}(D^{2-\epsilon})$ runtime guarantee. The dependency in D^2 of our bound is in this sense optimal. The proof of our result crucially relies on the analysis of an associated two-player game. We extend the guarantees of BFDN to: scenarios with limited memory and communication, adversarial setups where robots can be blocked, and exploration of classes of non-tree graphs. Finally, we provide a recursive version of BFDN with a runtime of $\mathcal{O}_\ell(n/k^{1/\ell}+\log(k)D^{1+1/\ell})$ for parameter $\ell \geq 1$, thereby improving performance for trees with large depth.

26. ***Mixing times of Markov chains: acceleration and cutoff in random environment*** [21]The aim of this dissertation is to explore various aspects concerning random walks and mixing times of Markov chains. First, our research introduces a novel technique called "linearization" in the analysis of random walks on discrete groups. Drawing inspiration from similar linearization approaches in operator algebras and random matrices, this opens up a whole new field of applications of this method. When a group is given by a finite set of generators, we show how linearization can simplify the study of finitely supported random walks by reducing to nearest-neighbour walks, at the cost of considering a slightly more general state space. We demonstrate the effectiveness of this technique by providing explicit formulas for asymptotic quantities like the speed and entropy of the walk, in the case of free groups and free products of finite groups. Our second contribution concerns a mechanism for accelerating Markov dynamics, consisting in inserting deterministic dynamics steps between the random steps of a Markov chain. When the deterministic dynamics is itself chosen randomly, it was proved that the mixing time becomes logarithmic in the size of the state space with high probability, which for many Markov chains implies an exponential speed-up. Our work attempts to "derandomize" this result by studying a multi-dimensional version of the historical example where such acceleration was first observed. In this explicit example, we thus suggest that the acceleration is the effect of the chaotic aspect of the applied deterministic dynamics. The third part of our work deals with the cutoff phenomenon, which is the abrupt convergence of a Markov chain towards equilibrium. We study a cutoff phenomenon for a chain in a random environment, a setting known to favor the phenomenon's appearance. The model studied consists in superposing two Markov chains on the same state space, one being subject to a uniform permutation of the states. Under mild assumptions we prove such chains exhibit a cutoff phenomenon at the so-called entropic time. In particular we do not assume reversibility or non-backtrackingness, which can be thought of as the opposite of reversibility. Until now, one or other of these assumptions was generally made in order to establish the cutoff phenomenon. We propose a unified proof strategy that bridges these opposing cases. This relies heavily on a novel measure concentration result for the symmetric group, developed explicitly for this problem, thereby making another contribution of this thesis.

27. ***LOS Coverage Area in Vehicular Networks with Cox-Distributed Roadside Units and Relays*** [3]We develop an analytical framework to examine the line-of-sight (LOS) coverage area in vehicular networks with roadside units (RSU) and vehicle relays. In practical deployment scenarios, RSUs and vehicle relays are spatially correlated and we characterize this by employing Cox point processes to model the locations of RSUs and vehicle relays simultaneously. Leveraging the random blockage model, we model the LOS coverage area as Boolean models on these Cox point processes. The LOS coverage area is then evaluated by its area fraction. We show that relays can increase the area fraction of LOS coverage by nearly 50% even when RSUs and relays are spatially correlated. By presenting a stochastic geometry model for a vehicular network with RSUs and relays and then by providing a tool to capture its LOS coverage, our work assesses the viability of vehicle relays for modern vehicular networks exploiting LOS coverage.

5.7 Random Geometry

28. ***Genealogies Of Records Of Stochastic Processes With Stationary Increments As Unimodular Trees*** [27] Consider a stationary sequence $X = (X_n)$ of integer-valued random variables with mean $m \in [-\infty, \infty]$. Let $S = (S_n)$ be the stochastic process with increments X and such that $S_0 = 0$. For each time i, draw an edge from (i, S_i) to (j, S_j), where $j > i$ is the smallest integer such that $S_j \geq S_i$, if such a j exists. This defines the record graph of X.

It is shown that if X is ergodic, then its record graph exhibits the following phase transitions when m ranges from $-\infty$ to ∞. For $m < 0$, the record graph has infinitely many connected components which are all finite trees. At $m = 0$, it is either a one-ended tree or a two-ended tree. For $m > 0$, it is a two-ended tree.

The distribution of the component of 0 in the record graph is analyzed when X is an i.i.d. sequence of random variables whose common distribution is supported on $\{-1, 0, 1, \ldots\}$, making S a skip-free to the left random walk. For this random walk, if $m < 0$, then the component of 0 is a unimodular typically re-rooted Galton-Watson Tree. If $m = 0$, then the record graph rooted at 0 is a one-ended unimodular random tree, specifically, it is a unimodular Eternal Galton-Watson Tree. If $m > 0$, then the record graph rooted at 0 is a unimodularised bi-variate Eternal Kesten Tree.

A unimodular random directed tree is said to be record representable if it is the component of 0 in the record graph of some stationary sequence. It is shown that every infinite unimodular ordered directed tree with a unique succession line is record representable. In particular, every one-ended unimodular ordered directed tree has a unique succession line and is thus record representable.

29. ***Poisson approximation of fixed-degree nodes in weighted random connection models*** [32] We present a process-level Poisson-approximation result for the degree-k vertices in a highdensity weighted random connection model with preferential-attachment kernel in the unit volume. Our main focus lies on the impact of the left tails of the weight distribution for which we establish general criteria based on their small-weight quantiles. To illustrate that our conditions are broadly applicable, we verify them for weight distributions with polynomial and stretched exponential left tails. The proofs rest on truncation arguments and a recently established quantitative Poisson approximation result for functionals of Poisson point processes.

30. ***Continuum percolation in a nonstabilizing environment*** [7]We prove phase transitions for continuum percolation in a Boolean model based on a Cox point process with nonstabilizing directing measure. The directing measure, which can be seen as a stationary random environment for the classical Poisson-Boolean model, is given by a planar rectangular Poisson line process. This Manhattan grid type construction features long-range dependencies in the environment, leading to absence of a sharp phase transition for the associated Cox-Boolean model. The phase transitions are established under individually as well as jointly varying parameters. Our proofs rest on discretization arguments and a comparison to percolation on randomly stretched lattices established in [Hof05].

31. ***Records of stationary processes and unimodular graphs*** [24]Consider a navigation rule defined on a graph that maps every vertex of the graph to a vertex in such a way that the navigation rule commutes with every automorphism of the graph. It is to say that the navigation rule applied to the vertices remains the same after taking any automorphism of the graph. Such a navigation rule is said to have the covariance property. This study delves into a collection of such covariant navigation rules, indexed by locally finite graphs, and subject to a measurability condition. This ensemble of rules is termed a vertex-shift. More generally, one can consider vertex-shifts on networks, graphs that have labels on edges and on vertices. A vertex-shift induces a dynamic on the space of locally finite rooted networks. The central focus of this work lies in investigating the dynamic associated to a specific navigation rule called the record vertex-shift. It is defined on the trajectories of any one dimensional discrete random walk whose increments have finite mean and the random walk can jump only one step to the left. Additionally, the work includes several notable results concerning record vertex-shifts applied to processes with stationary increments. The thesis also contains results on more general vertex-shifts on unimodular networks.

32. ***Unimodularity in Random Networks: Applications to the Null recurrent Doeblin Graph and Hierarchical Clustering*** [22]This thesis is based on the notion of unimodularity in the context of random networks and explores two domains of application: Coupling from the Past for Markov Chains in the null recurrent case based on the associated Doeblin Graphs, and unsupervised classification based on hierarchical clustering on point processes. The first part of this thesis focuses on the properties of a specific random graph called the Doeblin Graph, which is associated with the Coupling from the Past algorithm used for the perfect sampling of the stationary distribution of a Markov Chain. This thesis studies the null recurrent case, where it is shown that the Bridge Doeblin Graph, a subgraph of the Doeblin Graph, is either an infinite tree or a forest composed of a countable collection of infinite trees. In the former case, the infinite tree possesses a single end, is not generally unimodularizable, but exhibits local unimodularity. These properties are leveraged to in- vestigate the stationary regime of measure-valued random dynamics on the Bridge Doeblin Tree, particularly the taboo and potential random dynamics. The second part of this thesis introduces a novel hierarchical clustering model tailored for unsupervised classifications of datasets that are countably infinite. The proposed algorithm employs multiple levels of clustering, constructing clusters at each level using nearest- neighbor chains of points or clusters. This algorithm is applied to the Poisson point process. It is proven that the clustering algorithm defines a phylogenetic forest on the Poisson point process, which is a factor of the point process and is therefore unimodular. Various proper- ties of this random forest, such as the mean sizes of clusters at each level or the mean size of the cluster of a typical node, are examined.

5.8 Mathematics of stochastic networks via mean-field analysis

33. ***A decentralized algorithm for a Mean Field Control problem of Piecewise Deterministic Markov Processes*** [9]This paper provides a decentralized approach for the control of a population of N agents to minimize an aggregate cost. Each agent evolves independently according to a Piecewise Deterministic Markov dynamics controlled via unbounded jumps intensities. The N-agent high dimensional stochastic control problem is approximated by the limiting mean field control problem. A Lagrangian approach is proposed. Although the mean field control problem is not convex, it is proved to achieve zero duality gap. A stochastic version of the Uzawa algorithm is shown to converge to the primal solution. At each dual iteration of the algorithm, each agent solves its own small dimensional sub problem by means of the Dynamic Programming Principal, while the dual multiplier is updated according to the aggregate response of the agents. Finally, this algorithm is used in a numerical simulation to coordinate the charging of a large fleet of electric vehicles in order to track a target consumption profile.

34. *Mean field analysis of stochastic networks with reservation* [29]The problem of reservation in a large distributed system is analysed via a new mathematical model. The target application is car-sharing systems. This model is precisely motivated by the large station-based car-sharing system in France, called Autolib'. This system can be described as a closed stochastic network where the nodes are the stations and the customers are the cars. The user can reserve the car and the parking space. In the paper, we study the evolution of the system when the reservation of parking spaces and cars is effective for all users. The asymptotic behaviour of the underlying stochastic network is given when the number N of stations and the fleet size M increase at the same rate. The analysis involves a Markov process on a state space with dimension of order N^2 . It is quite remarkable that the state process describing the evolution of the stations, whose dimension is of order N , converges in distribution, although not Markov, to an non-homogeneous Markov process. We prove this mean-field convergence. We also prove, using combinatorial arguments, that the mean-field limit has a unique equilibrium measure when the time between reserving and picking up the car is sufficiently small. This result extends the case where only the parking space can be reserved.

35. *An incentive algorithm for a closed stochastic network: data and mean-field analysis* [33]The paper deals with a load-balancing algorithm for a closed stochastic network with two zones with different demands. The algorithm is motivated by an incentive algorithm for redistribution of cars in a large-scale car-sharing system. The service area is divided into two zones. When cars stay too long in the low-demand zone, users are encouraged to pick them up and return them in the high-demand zone. The zones are divided in cells called stations. The cars are the network customers. The mean-field limit solution of an ordinary differential equation (ODE) gives the large scale distribution of the station state in both clusters for this incentive policy in a discrete Markovian framework. An equilibrium point of this ODE is characterized via the invariant measure of a random walk in the quarter-plane. The proportion of empty and saturated stations measures how the system is balanced. Numerical experiments illustrate the impact of the incentive policy. Our study shows that the incentive policy helps when the high-demand zone observes a lack of cars but a saturation must be prevented especially when the high-demand zone is small.

36. *Point-process-based Markovian dynamics and their applications* [20] In this thesis, we are interested in mathematical models of phenomena that can be interpreted as network dynamics. This includes for example neuron population models in which neurons interact at random times with their neighbors or epidemics propagation where infected or susceptible individuals move from town to town. The mathematical description of such phenomena generally requires a compromise between physical or biological relevance and mathematical tractability. The main focus of this work is the elaboration of mathematical proofs to justify the introduction of models taking into account the geometry of the underlying networks whilst preserving tractability. The main mathematical tool for that purpose is the replica-mean-field, which consists in copies of the studied network between which interactions are routed randomly. The main results of this thesis concern the behavior of such a dynamical system when the number of replicas goes to infinity. In various settings, we show that it concerges to dynamics under the Poisson Hypothesis, that is, interaction times are replaced by independent Poisson processes, which allows to obtain closed forms in certain models. In chapter 2 of the thesis, we prove this result for a class of discrete-time dynamics: fragmentation-interaction-aggregation processes. At the scale of a given node, theses processes model its state by an autonomous evolution to which are aggregated the effets of the interactions with its neighbors. Chapter 3 extends these results to the continuous-time framework, where interaction times are seen as realizations of point processes, highlighting the case of Galves-Löcherbach model used in computational neuroscience. Finally, chapter 4 focuses on the study of a model of epidemics propagation under the Poisson Hypothesis: the migration-contagion process, consisting in a closed network of queues in between which infected and susceptible customers migrate. More precisely, we establish a system of nonlinear equations verified by the mean numbers of infected and susceptible individuals in the objective of studying it numerically.

37. *A new stochastic model for carsharing suited to free-floating* [30] Free-floating has an increasing popularity in carsharing but imbalance problem shows the need of stochastic modelling and analysis. In this paper, a new stochastic model suited to free-floating is proposed, taking into account the sharing of public space between private and free-floating cars.The capacity seen by free-floating cars in such a model turns out to be random. We show that unlike station-based car-sharing systems, it is not bounded. Moreover, a stochastic averaging principle governs the free-floating car behavior. We exhibit a phase transition between a non-saturated regime where free-floating cars can always be parked and a saturated one where free-floating cars do not find an available parking space with positive probability. This probability is completely determined by the environment which implies that the operator cannot act on the proportion of saturated areas, i.e. without parking parking spaces. We solve the dimensioning problem; the more free-floating cars in the system, the more satisfied users are.

6 Bilateral contracts and grants with industry

6.1 Bilateral contracts with industry

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Ana Bušić, Guodong Sun.

6.1.1 Contract with EDF

Collaborative research in the area of demand dispatch of flexible loads. PI: A. Bušić.

6.1.2 CRE with Orange Labs

Two year contract titled *Guaranteed throughput and millimeter waves in the dimensioning of 5G cellular networks* between Inria and Orange Labs started 2022 and attached to the joint Inria-Orange lab "IOLab". It is a part of a long-term collaboration between TREC/DYOGENE, represented by B. Błaszczyszyn and Orange Labs, represmnted by M. K. Karray on the development of mathematical methods and engineering analytical tools for the dimensioning of wireless cellular networks enabling operators to solve critical technical and economic issues related to the main business related to the permanent evolution of radio technology. They capture the macroscopic relation between antenna deployment, frequency allocation, the volume of traffic carried on the network, and QoS parameters, such as the average and variation in bandwidth available to end users. The math solutions developed in cooperation with Orange Labs are implemented by Orange Labs in their internal toolbox and used for dimensioning studies by *Direction des Affaires Réglementaires* of Orange, *Orange France* in relation to ARCEP (*Autorité de Régulation des Communications Électroniques, des Postes et de la Distribution de la Presse*) and Orange affiliates.

6.1.3 CIFRE with Nokia Bell Labs

Contract with Nokia Bell Labs France started in 2021 for the co-advising by F. Baccelli of a PhD student Guodong Sun.

7 Partnerships and cooperations

7.1 International initiatives

7.1.1 IFCAM poject

Participants: Bartłomiej Błaszczyszyn, Romain Gambelin.

Indo-French Centre for Applied Mathematics IFCAM project Geometric statistics of stationary point processes started in 2018 and extended to March 2023 with coordinators B. Błaszczyszyn (Inria), Yogeshwaran D. (ISI Bangalore). The project is investigating the asymptotic properties of the geometric statistics of point processes, which have recently gained importance in stochastic geometry, in particular for more general point processes, for which theory still lags far behind Poisson point processes. This year R. Gambelin wisited ISI Bangalore and we have hosted Prof. Yogeshwaran D. and his studend.

7.1.2 Alliance Communauto Montreal

Participants: Christine Fricker.

Dyogene participates in 4-year research project (2023-2027) co-funded by Communauto, NSERC and MItacs in Montreal.

7.2 International research visitors

Scientists speaking at the DYOGENE's seminar in 2023:

- Raphaël Lachièze-Rey (Université Paris Descartes)
- Ayoub Belhadji (L'équipe Ockham, LIP, ENS de Lyon)
- Pascal Moyal (IECL - Université de Lorraine)
- Philippe Robert (Inria Paris)
- D.Yogeshwaran (Indian Statistical Institute, Bangalore)
- Leo Dort (ENS Lyon)
- David McDonald (University of Ottawa)
- Takis Konstantopoulos (University of Liverpool)
- Giovanni Luca Torrisi (CNR-IAC, Roma, Italy)
- Lewis Bowen (University of Texas at Austin)
- Stephane Gaubert (INRIA et CMAP, Ecole polytechnique, IP Paris)
- Elizabeth O'Reilly (California Institute of Technology)
- Adam Timar (University of Iceland; Alfred Renyi Institute of Mathematics)
- Venkat Anantharam (EECS Department, University of California, Berkeley)
- Thomas Budzinski (ENS de Lyon)
- Eyal Castiel (Georgia Tech)
- Charles Bordenave (CNRS Marseille)
- Pierre Calka (Université de Rouen)
- Nicolas Curien (Université Paris Saclay)
- Laurent Decreusefond (Télécom Paris)
- Sergey Foss (Heriot Watt University, UK)
- Nicolas Gast (INRIA Grenoble)
- Alexandre Gaudillière (CNRS Marseille)
- Eva Löcherbach (Université Paris Panthéon Sorbonne)
- Eric Luçon (Université Paris Cité)
- Ravi R. Mazumdar (University of Waterloo, Canada)
- Hermann Thorisson (University of Iceland)

Inria International Chair

Participants: Ana Busic, Sean Meyn.

Prof Sean Meyn (University of Florida) is holding Inria International Chair from 2019 to 2023 in association with Dyogene and Sierra teams.

7.3 European initiatives

7.3.1 ERC NEMO

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Bharath Roy Choudhury, Ke Feng, Sayeh Khaniha, Ali Khezeli, Pierre Popineau, Sanjoy Kumar Jhawar.

NEMO NEtwork MOtion, Inria/NEMO is an ERC Advanced Grant (2019–2024, PI François Baccelli). It is an inter-disciplinary proposal centered on network dynamics. The inter-disciplinarity spans from communication engineering to mathematics, with an innovative interplay between the two. NEMO's aim is to introduce dynamics in stochastic geometry. General mathematical tools combining stochastic geometry, random graph theory, and the theory of dynamical systems will be developed. NEMO leverages interactions of Inria with Ecole Normale Supérieure on the mathematical side, and with Nokia Bell Labs and Orange on the engineering side.

This year NEMO organized a Workshop on "Performance Guarantees in Wireless Networks", at LINCS, March 8-9, 2023, and a Workshop 8 Days on Network Mathematics at Inria, September 18-27, 2023.

7.3.2 SNS INSTINC

Participants: François Baccelli.

Smart Networks and Services(SNS) The Smart Networks and Services Joint Undertaking In November 2021, Council Regulation 2021/2085 established the SNS JU to drive Europe's green and digital transition. with a €900 million EU budget for 2021-2027. The SNS JU has two main missions: by pooling EU and industrial resources advancing Europe's 6G technology leadership and accelerating 5G deployment. On January 17, 2023 the SNS JU launched its second Research & Innovation Work Programme for 6G research in Europe, with €132 million in earmarked public funding. Inria had funding for its individual program structured by Jean-Marie Gorce at INSA-Lyon. F. Baccelli participates in in this program through the SNS INSTINC project on *joint communications and services*.

7.3.3 Collaboration with VITO (Belgium)

Participants: Ana Busic, Ilia Shilov.

Collaboration with VITO Belgium. Co-advising of PhD student I. Shilov. Started: Nov 2019. Topic: "Algorithmic Games and Distributed Learning for Peer-to-Peer Energy Trading". PhD scholarship by VITO.

7.4 National initiatives

7.4.1 PEPR "5G et Réseaux du Futur"

Participants: François Baccelli, Bartłomiej Błaszczyszyn.

As a part of the national "Programmes et équipements prioritaires de recherche" (PEPR), «5G et Réseaux du Futur» project is led by Institut Mines-Télécom, CEA, and CNRS as the leaders. (Inria is a partner but is not leading this project.) It is made up of 10 projects (PC1 to PC10). (Inria teams are involved in several of these projects.) F. Baccelli and J-M. Gorce carried the PC9 project, which is focused on *theoretical tools and fundamental limits*. F. Baccelli will be the coordinator of this project, for Inria. The launch took place on July 10-11-12 2023.

7.4.2 PRAIRIE Institute

Participants: Marc Lelarge, Laurent Massoulié.

The Prairie Institute (PaRis AI Research InstitutE) is one of the four French Institutes for Interdisciplinary Artificial Intelligence Research (3IA), which were created as part of the national French initiative on AI announced by President Emmanuel Macron on May 29, 2018. It brings together five academic partners (CNRS, Inria, Institut Pasteur, PSL University, and University of Paris) as well as 14 industrial partners.

7.4.3 GdR GeoSto

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Bharath Roy Choudhury, Michel Davydov, Romain Gambelin, Sayeh Khaniha, Ali Khezeli, Gabriel Mastrilli.

Members of Dyogene participate in Research Group GeoSto (Groupement de recherche, GdR 3477) gdr-geostoch.math.cnrs.fr on Stochastic Geometry currenly led by Hermine Biermé [Université de Tours]. 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.

7.4.4 GdR RO

Participants: Ana Busic, Thomas Le Corre, Lucas Weber.

Members of Dyogene participate in the group Recherche Opérationelle GdR-RO working on Stochastic optimization and control, modeling and simulation COSMOSlead by A. Busic and E. Hyon (LIP 6).

7.4.5 Défi Inria FedMalin

Participants: Kevin Scaman, Laurent Massoulié.

Members of Dyogene participate in the FedMalin Inria défi on Federated Learning.

7.4.6 Défi INRIA-AP-HP Urge

Participants: Christine Fricker.

Dyogene participates in the URGE Inria-AP-HP défi on optimisation of care management in emergency departments.

7.5 Regional initiatives

7.5.1 LINCS

Participants: All Dyogene.

Dyogene participates in Laboratory of Information, Networking and Communication Sciences LINCS, a research centre co-founded by Inria, Institut Mines-Télécom, UPMC and Alcatel-Lucent Bell Labs (currently Nokia Bell Labs) dedicated to research and innovation in the domains of future information and communication networks, systems and services.

8 Dissemination

Participants: All Dyogene.

8.1 Promoting scientific activities

8.1.1 LINCS+NEMO Performance Guarantees in Wireless Networks

This year NEMO organized a Workshop on "Performance Guarantees in Wireless Networks", at LINCS, March 8-9, 2023. The Workshop dealt with a central problem for the new generations of wireless networks which is that of real-time type guarantees. These guarantees are necessary for industrial applications of 5G and 6G. Deterministic guarantees are essential for critical real-time. This workshop showed that the problem required fundamental contributions from several areas covered by the following invited speakers:

- JEAN-MARIE GORCE (INSA LYON / INRIA LYON) – Performance guarantees in a wireless cell with massive access: beyond capacity with non asymptotic information theory,
- DERYA MALAK (EURECOM) – The Interplay of Spectral Efficiency, User Density, and Energy in Random Access Protocols,
- LAURENT CLAVIER (IMT NORD EUROPE) – Some words about interference, SAMIR M. PERLAZA (INRIA SOPHIA) – An Upper Bound on the Error Induced by Saddlepoint Approximations—Applications to Wireless Communications,
- EMMANUEL BOUTILLON (UNIVERSITÉ DE BRETAGNE SUD) – Quasi Cyclic Short Packets for unslotted aloha transmission,
- MAXIME GUILLAUD (INRIA LYON) – Towards Practical Waveforms for Massive Random Access,
- PHILIPPE MARY (CNRS RENNES) – Increasing the performance of polar codes at short blocklength,
- CHARLY POULLIAT (CNRS TOULOUSE) – Power efficient Communications: asymptotic versus finite length error correcting schemes performance,
- JEAN-YVES LEBOUDEC (EPFL) – Time Sensitive Networks and Network Calculus and Clock Non-idealities,
- KE FENG (INRIA PARIS) – Spatial Network Calculus and Performance Guarantees in Wireless Networks,

- MARIOS KOUNTOURIS (EURECOM) – Goal-oriented Communication for Distributed Intelligent Systems,
- MICHÈLE WIGGER (TÉLÉCOM-PARIS) – Capacity-Tradeoffs in Networks with Mixed-Delay Traffics and Random Arrivals,
- MARCO DI RENZO (CENTRALE SUPELEC) – Analysis of the Delay Distribution in Cellular Networks by Using Stochastic Geometry,
- MARCEAU COUPECHOUX AND BENOÎT-MARIE ROBAGLIA (TÉLÉCOM-PARIS) – Deep Reinforcement Learning for Multiple Access in uplink URLLC networks,
- SALAH ELAYOUBI (CENTRALE SUPELEC) – Rediscovering Aloha for latency-critical services: the blind and the far-sighted,
- INBAR FIJALKOW (CNRS CERGY) – NOMA uplink networks under statistical delay constraints.

8.1.2 Inria+NEMO 8 Days on Network Mathematics

This year NEMO organized a workshop 8 Days on Network Mathematics at Inria, September 18-27, 2023. This informal international workshop will focus on stochastic networks, spatial stochastic processes, and their dynamics. It will feature three thesis defenses (of B. Roy Choudhury, M. Davydov and S. Khaniha) and and a series of one-hour lectures delivered by researchers actively engaged in the field:

- Charles Bordenave (CNRS Marseille)
- Pierre Calka (Université de Rouen)
- Nicolas Curien (Université Paris Saclay)
- Laurent Decreusefond (Télécom Paris)
- Sergey Foss (Heriot Watt University, UK)
- Nicolas Gast (INRIA Grenoble)
- Alexandre Gaudillière (CNRS Marseille) Eric Luçon (Université Paris Cité)
- Eva Löcherbach (Université Paris Panthéon Sorbonne)
- Ravi R. Mazumdar (University of Waterloo, Canada)
- Hermann Thorisson (University of Iceland)

8.1.3 Scientific events: organisation

- The 21st INFORMS Applied Probability Society Conference will be held on June 28-30, 2023 in Nancy, France Organizing invited sessions:
  - Infinite-dimensional queueing/communication systems (F. Baccelli and S. Foss [Heriot-Watt University, United Kingdom])
  - Mean-field approach for analysis of complex stochastic systems II (C. Fricker)
  - Stochastic matching and applications (A. Busic)
  - Graph matching and planted models in random graphs (M. Lelarge)

8.1.4 Invited talks

- K. Feng, "Spatial Network Calculus and Performance Guarantees in Wireless Networks". Invited Talk at Workshop on Performance Guarantees in Wireless Networks, Mar 2023,Palaiseau
- C. Fricker, invited lecture on "Stochastic networks and mean-filed limits" at ALEA Days, CIRM Luminy, France, March 13-17, 2023, C. Fricker.
- F. Baccelli, Invited lecture on wireless stochastoc geometry at Tampere University, Finland, April 23.
- B. Blaszczyszyn, invited talk on "Ergodic learning of point processes" Stochastic Models VII, May 2023, Bedlewo, Poland
- F. Baccelli, Keynote lecture at the KICS workshop on stochastic geometry, Seoul, May 23.
- F. Baccelli, Invited lecture at Korea University on real time communications, May 23.
- F. Baccelli, Invited lecture at Yonsei University on wireless communications, May 23.
- F. Baccelli, Invited lecture at Online General Seminar at CNR, on high dimensional geometry in the Shannon regime, May 23, Rome.
- K. Feng, "Spatial Network Calculus and Performance Guarantees in Wireless Networks". Invited Talk at 2023 LINCS Annual Workshop, Jul 2023, Palaiseau
- Presentation of the FOUNDS Prject, PEPR réseaux du Futur, PEPR Kickoff meeting, Palaiseau, July 23.
- F. Baccelli, Presentation of the FOUNDS Prject, PEPR réseaux du Futur, PEPR Kickoff meeting, Palaiseau, July 23.
- K. Feng, "Spatial Network Calculus and Performance Guarantees in Wireless Networks". 2023 21st International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Aug 2023, Singapore
- F. Baccelli, Plenary lecture on unimodular ramdom networks at the 2023 Brazilian School of Probability, August 23, Sao Paulo, Brasil.
- B. Blaszczyszyn, invited lecture on "Limit theory for asymptotically de-correlated spatial random models" at confeence on New Perspectives in the Theory of Extreme Values Dubrovnik, October, 2023.
- K. Feng, "Spatial Network Calculus and Performance Guarantees in Wireless Networks", Invited Talk, Séminaire ETIS-ICI, Oct 2023, Cergy
- F. Baccelli, Invited conference on Stochastic Geometry for 6G at SRIA Fourth Visions for Future Communications Summit November 2023, Lisbonne, Portugal
- C. Fricker, Invited lecture on "Fluid limit for a M/G/infini queue with advance booking, booking cancelation and reneging" at SPOR Seminar, TU Eindhoven, Netherlands, December 2023, C. Fricker.

8.1.5 Scientific expertise

- B. Blaszczyszyn: reviewer of German Research Foundation (DFG) of Priority Programme "Random Geometric Systems" SPP 2265 2023.

8.2 Teaching - Supervision - Juries

8.2.1 Teaching

- Licence: B. Błaszczyszyn (Cours) Théorie de l'information et du codage 24 heqTD, L3, ENS Paris. moodle.psl.eu
- Licence: A. Busic (Cours) and Romain Cosson (Cours + TD) Structures et algorithmes aléatoires 60 heqTD, L3, ENS Paris.
- Licence: M. Davydov (Cours) Introduction aux probabilités (L2 Mathématiques) 38h(eqTD) and Bases des mathématiques : semaine de prérentrée (L1 Mathématiques & Informatique) 15h(eqTD), University Paris-Cité.
- Licence: R. Gambelin, CM de "Probabilités approfondies" en seconde année de la CPES de PSL (filière mathématiques et physique).
- Licence: L. Massoulié (Cours) Social and Communication networks 60 heqTD, L3, l'X.
- Master: B. Błaszczyszyn (Cours) "Random Geometric Models", jointly at M2 "Probabilities and Random Models", Sorbonne University and M2 "Applied and Theoretical Mathematics", University Paris-Dauphine-PSL (39heqTD). moodle.psl.eu
- Master: A. Busic (Cours) and L. Weber (TD) Modèles et algorithmes de réseaux 60 heqTD, M1, ENS Paris.
- Master: A. Busic and L. Massoulié (Cours) Fondements de la modélisation des réseaux 37.5 heqTD, M2 MPRI.
- Master: M. Lelarge (Cours) Deep Learning Do it Yourself, X, X-HEC. mlelarge.github.io/dataflowr-web/
- Master: L. Massoulié (Cours) Inference in large random graphs, M2 Université d'Orsay.
- Master: K. Scaman with the participation of M. Lelarge (Cours) Deep Learning, 24 heqTD, M1, ENS Paris.
- Master: K. Scaman (Cours) and M. Even (TD) Mathematics of Deep Learning, 30 heqTD, M2 MASH, Université Dauphine.
- Master: K. Scaman (TD) Machine Learning 2, 21 heqTD, M2 X-HEC, Institut Polytechnique de Paris.
- Master: R. Gambelin, Chargé de TD "Méthodes quantitatives", L2 Eco & Gestion, l'université Paris Descartes.

8.2.2 Supervision

PhD defended:

- Pierre Popineau, "Study of the dynamics of spatial point processes in wireless communication networks" [23], defended in June 2023, supervised by F. Baccelli
- Michel Davydov, "Point-process-based Markovian dynamics and their applications" [20], defended in September 2023, supervised by F. Baccelli
- Bharath Roy, "Records of stationary processes and unimodular graphs" [24], defended September 2023, supervised by F. Baccelli
- Sayeh Khaniha, "Unimodularity in Random Networks: Applications to the Null recurrent Doeblin Graph and Hierarchical Clustering" [22] defended in September 2023, supervised by F. Baccelli
- Ilia Shilov, "Game-Theoretic Approaches for Peer-to-Peer Energy Trading", [25], defended in September 2023, supervised by A. Bušić,

- Bastien Dubail, "Mixing times of Markov chains: acceleration and cutoff in random environment" [21], defended in October 2023,supervised by Laurent Massoulié

PhD in progress:

- Claire Bizon Monroc, since Nov 2021, supervised by A. Bušić
- Matthieu Blanke since Sep 2021, supervised by M. Lelarge
- Pascal Capitello, since Nov 2023, supervised by C. Fricker
- Romain Cosson, since Sep 2022, supervised by Laurent Massoulié
- Mathieu Even since Sep 2021, supervised by Laurent Massoulié
- Roman Gambelin since Sep 2020, supervised by B. Blaszczyszyn
- Cedric Gerbelot since Sep 2021, supervised by M. Lelarge
- Thomas Le Corre since Nov 2021, supervised by Bušić
- Maxime Leiber since Feb 2020, supervised by Laurent Massoulié
- Jakob Maier, since Oct 2022, supervised by Laurent Massoulié
- Alessia Rigonat since Oct 2023, supervised by C. Fricker
- David Robin, since Oct 2021, supervised by Laurent Massoulié
- Guodong Sun, since 2021, supervised by F. Baccelli
- Amaury Triboulin since Sep 2021, supervised by M. Lelarge
- Lucas Weber since Oct 2021, supervised by A. Bušić
- Gabriel Mastrilli since September 2023, supervised by B. Blaszczyszyn

8.2.3 Juries

- C. Fricker: member of the thesis committee of Diego Goldstajn (UTE, Eindhoven, Netherlands).
- B. Blaszczyszyn: PhD juries of Bharath Roy and Ilia Shilov (Inria).

8.3 Popularization

- Jakob Maier, co-organization of "Rencontres Jeunes Mathématiciennes et Informaticiennes", Inria Paris, October 2023
- Killian Bakong, Claire Bizon-Monroc, Alessia Rigonat, Entertainers of "Rencontres Jeunes Mathématiciennes et Informaticiennes", Inria Paris, October 2023

9 Scientific production

9.1 Publications of the year

International journals

[1] B. Blaszczyszyn, P. Jacquet, B. Mans and D. Popescu. 'Energy and Delay Trade-Offs of End-to-End Vehicular Communications using a Hyperfractal Urban Modelling'. In: *Annals of Telecommunications - annales des télécommunications*. special issue on 5+G Network Energy Consumption, Energy Efficiency and Environmental Impact (2023). DOI: 10.1007/s12243-022-00939-2. URL: https://hal.science/hal-03942997.

[2] N. Cammardella, A. Bušić and S. Meyn. 'Kullback–Leibler-Quadratic Optimal Control'. In: *SIAM Journal on Control and Optimization* 61.5 (25th Oct. 2023), pp. 3234–3258. DOI: 10.1137/21M1433654. URL: https://inria.hal.science/hal-04476982.

[3] C.-S. Choi and F. Baccelli. 'LOS Coverage Area in Vehicular Networks with Cox-Distributed Roadside Units and Relays'. In: *IEEE Transactions on Vehicular Technology* 72.6 (June 2023), pp. 7772–7782. DOI: 10.1109/TVT.2023.3238730. URL: https://hal.science/hal-04451961.

[4] A. Coffman, A. Bušić and P. Barooah. 'A unified framework for coordination of thermostatically controlled loads'. In: *Automatica* 152 (June 2023), p. 111002. DOI: 10.1016/j.automatica.2023.111002. URL: https://hal.science/hal-03541767.

[5] M. Even, S. Pesme, S. Gunasekar and N. Flammarion. '(S)GD over Diagonal Linear Networks: Implicit Regularisation, Large Stepsizes and Edge of Stability'. In: *Advances in Neural Information Processing Systems* (25th Oct. 2023). URL: https://inria.hal.science/hal-04435173.

[6] K. Feng and F. Baccelli. 'Spatial Network Calculus and Performance Guarantees in Wireless Networks'. In: *IEEE Transactions on Wireless Communications* (19th Oct. 2023). DOI: 10.1109/TWC.2023.3324069. URL: https://inria.hal.science/hal-04435272.

[7] B. Jahnel, S. K. Jhawar and A. D. Vu. 'Continuum percolation in a nonstabilizing environment'. In: *Electronic Journal of Probability* 28 (27th Oct. 2023), pp. 1–38. DOI: 10.1214/23-ejp1029. URL: https://hal.science/hal-04434440.

[8] J. Mathias, A. Bušić and S. Meyn. 'Load-Level Control Design for Demand Dispatch With Heterogeneous Flexible Loads'. In: *IEEE Transactions on Control Systems Technology* 31.4 (July 2023), pp. 1830–1843. DOI: 10.1109/TCST.2023.3245287. URL: https://hal.science/hal-04450087.

[9] A. Séguret, T. Le Corre and N. Oudjane. 'A decentralized algorithm for a Mean Field Control problem of Piecewise Deterministic Markov Processes'. In: *ESAIM: Probability and Statistics* 28 (12th Jan. 2024), pp. 22–45. DOI: 10.1051/ps/2023021. URL: https://hal.science/hal-03910622.

International peer-reviewed conferences

[10] M. Blanke and M. Lelarge. 'FLEX: an Adaptive Exploration Algorithm for Nonlinear Systems'. In: *Proceedings of the 40th International Conference on Machine Learning, PMLR*. ICML 2023 - International Conference on Machine Learning. Vol. 202. Honolulu, Hawaii, United States, 23rd July 2023, pp. 2577–2591. URL: https://hal.science/hal-04176336.

[11] A. Bušić and J.-M. Fourneau. 'Stochastic Matching Model with Returning Items'. In: ASMTA/EPEW: The 27th International Conference on Analytical & Stochastic Modelling Techniques & Applications / 19th European Performance Engineering Workshop. Vol. 14231. Lecture Notes in Computer Science. Florence, Italy: Springer Nature Switzerland, 7th Oct. 2023, pp. 186–200. DOI: 10.1007/978-3-031-43185-2_13. URL: https://inria.hal.science/hal-04476980.

[12] A. Bušić, S. Meyn and N. Cammardella. 'Learning Optimal Policies in Mean Field Models with Kullback-Leibler Regularization'. In: *2023 62nd IEEE Conference on Decision and Control (CDC)*. 2023 62nd IEEE Conference on Decision and Control (CDC). Singapore, Singapore: IEEE, 13th Dec. 2023, pp. 38–45. DOI: 10.1109/CDC49753.2023.10383868. URL: https://inria.hal.science/hal-04476983.

[13] C.-S. Choi and F. Baccelli. 'Extending the LOS Coverage of Vehicular Networks Based on Roadside Units and Vehicle Relays'. In: ICC 2023 - IEEE International Conference on Communications. Rome, Italy: IEEE, 28th May 2023, pp. 3977–3982. DOI: 10.1109/ICC45041.2023.10279796. URL: https://hal.science/hal-04451973.

[14] R. Cosson, L. Massoulie and L. Viennot. 'Brief Announcement: Efficient Collaborative Tree Exploration with Breadth-First Depth-Next'. In: PODC '23: 2023 ACM Symposium on Principles of Distributed Computing. Orlando FL, United States: ACM, 16th June 2023, pp. 24–27. DOI: 10.1145/3583668.3594568. URL: https://hal.science/hal-04429961.

[15] R. Cosson, L. Massoulié and L. Viennot. 'Efficient Collaborative Tree Exploration with Breadth-First Depth-Next'. In: International Symposium on Distributed Computing (DISC 2023). L'aquila, Italy: Schloss Dagstuhl – Leibniz-Zentrum für Informatik, 2023. DOI: 10.4230/LIPIcs.DISC.2023.14. URL: https://hal.science/hal-04427770.

[16] H. P. Keeler, B. Blaszczyszyn and E. Cali. 'Connectivity and interference in device-to-device networks in Poisson-Voronoi cities'. In: WiOpt 2023 - 21st International Symposium on Modeling and Optimization in Mobile, Ad hoc, and Wireless Networks. Singapore, Singapore, 5th Sept. 2023. URL: https://inria.hal.science/hal-04190745.

[17] C. Lauand, A. Bušić and S. Meyn. 'Inverse Free Zap Stochastic Approximation Extended Abstract'. In: *2023 59th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*. 2023 59th Annual Allerton Conference on Communication, Control, and Computing (Allerton). Monticello, United States: IEEE, 2023, pp. 1–4. DOI: 10.1109/Allerton58177.2023.10313420. URL: https://inria.hal.science/hal-04476981.

[18] J. Maier and L. Massoulié. 'Asymmetric tree correlation testing for graph alignment'. In: *Proceedings of the 2023 IEEE Information Theory Workshop (ITW)*. 2023 IEEE Information Theory Workshop (ITW). Saint-Malo, France: IEEE, 28th Apr. 2023, pp. 503–508. DOI: 10.1109/ITW55543.2023.10161653. URL: https://hal.science/hal-04435165.

[19] L. Weber, A. Bušić and J. Zhu. 'Reinforcement learning based demand charge minimization using energy storage'. In: 62nd IEEE Conference on Decision and Control (CDC). Singapore, Singapore: IEEE, Dec. 2023, pp. 4351–4357. DOI: 10.1109/CDC49753.2023.10383414. URL: https://inria.hal.science/hal-04433261.

Doctoral dissertations and habilitation theses

[20] M. Davydov. 'Point-process-based Markovian dynamics and their applications'. Ecole normale supérieure PSL, 25th Sept. 2023. URL: https://theses.hal.science/tel-04268154.

[21] B. Dubail. 'Mixing times of Markov chains: acceleration and cutoff in random environment'. Ecole Normale Superieure, 13th Oct. 2023. URL: https://inria.hal.science/tel-04434707.

[22] S. Khaniha. 'Unimodularity in Random Networks: Applications to the Null recurrent Doeblin Graph and Hierarchical Clustering'. Ecole normale superieure, 26th Sept. 2023. URL: https://inria.hal.science/tel-04431608.

[23] P. Popineau. 'Study of the dynamics of spatial point processes in wireless communication networks'. Université Paris sciences et lettres, 14th June 2023. URL: https://theses.hal.science/tel-04496165.

[24] B. Roy Choudhury. 'Records of stationary processes and unimodular graphs'. Ecole normale supérieure PSL, 18th Sept. 2023. URL: https://inria.hal.science/tel-04426692.

[25] I. Shilov. 'Game-Theoretic Approaches for Peer-to-Peer Energy Trading'. École Normale Supérieure, PSL University, 20th Sept. 2023. URL: https://theses.hal.science/tel-04371365.

Reports & preprints

[26] B. Ana, C. Arnaud, J. Doncel and F. Jean-Michel. *Performance Paradox of Dynamic Matching Models under Greedy Policies*. 22nd June 2023. URL: https://hal.science/hal-04137823.

[27] F. Baccelli and B. Roy Choudhury. *Genealogies Of Records Of Stochastic Processes With Stationary Increments As Unimodular Trees*. 11th Mar. 2024. URL: https://inria.hal.science/hal-04497843.

[28] C. Comte, F. Mathieu and A. Bušić. *Stochastic dynamic matching: A mixed graph-theory and linear-algebra approach*. 25th June 2023. URL: https://hal.science/hal-03502084.

[29] C. Fricker and H. Mohamed. *Mean field analysis of stochastic networks with reservation*. 14th Nov. 2023. URL: https://hal.science/hal-03539104.

[30] C. Fricker, H. Mohamed, A. Rigonat and M. Trépanier. *A new stochastic model for carsharing suited to free-floating*. 3rd Feb. 2024. URL: https://hal.science/hal-03938964.

[31] L. Ganassali, L. Massoulié and G. Semerjian. *Statistical limits of correlation detection in trees*. 3rd Jan. 2023. URL: https://hal.science/hal-03920990.

[32] C. Hirsch, B. Jahnel, S. K. Jhawar and P. Juhász. *Poisson approximation of fixed-degree nodes in weighted random connection models*. 21st Nov. 2023. URL: https://hal.science/hal-04434459.

[33] B. Marin Moreno, C. Fricker, H. Mohamed, A. Philippe and M. Trépanier. *An incentive algorithm for a closed stochastic network: data and mean-field analysis*. 23rd Nov. 2023. URL: https://hal.science/hal-04437641.

[34] P. Moyal, A. Busic and J. Mairesse. *On the sub-additivity of stochastic matching*. 29th Apr. 2023. URL: https://hal.science/hal-04088419.

[35] I. Shilov, H. Le Cadre, A. Bušić and G. de Almeida Terça. *A Stackelberg Game Analysis of Risk-Hedging Strategies in Decentralized Electricity Markets*. 16th Jan. 2023. URL: https://hal.science/hal-03674562.