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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

Contents

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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- Ana Busic [Inria, Researcher]
- Christine Fricker [Inria, Researcher, HDR]
- Mir Omid Haji Mirsadeghi [Inria, Advanced Research Position, from Nov 2021]
- Ali Khezeli [Inria, Starting Research Position]
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- Marc Olivier Buob [Bell Labs (Alcatel)]
- Fabien Mathieu [Nokia, HDR]

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

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 F. Baccelli and B. Blaszczyszyn.
- 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 2021 are summarized in the following sections.

3.2 Models of infectious diseases

Over the past years, with several researchers and collaborations with we have looked at mathematical models of the evolution of the epidemics, in particular Covid 19. This year we studied the role of geographic mobility on the propagation of epidemics using point process techniques, see [4].

3.3 Distributed network control and smart-grids

Theory and algorithms for distributed control of networks with applications to the stabilization of power grids subject to high volatility of renewable energy production are being developed by A. Busic in collaboration with Sean Meyn [Prof. at University of Florida and Inria International Chair] and Prabir Barooah [University of Florida]. We extended the Kullback-Leibler-quadratic optimal control approach to the case of stochastic disturbance. Also new advances have been obtained for thermostatically controlled loads. Within our collaboration with Vito (Belgium) that started in 2019 the main focus in 2021 has been on the Generalized Nash Equilibrium models for P2P markets.

3.4 Reinforcement learning

This year, in a book chapter [29], we reviewed the foundations of reinforcement learning algorithm design based on recent and more classical results from stochastic approximation. A new collaboration with IFPEN started on reinforcement learning with constraints and applications to wind farm production optimization, with PhD thesis of Claire Bizon Monroc.

3.5 Mathematics of wireless cellular networks

This year we revisited our previous line of thought on probabilistic modeling of geographic caching in wireless networks, by contributing a chapter [30] to the book with editors V. Poor [Princeton University] and W. Chen [Tsinghua University], www.bibliovault.org/BV.book.epl?ISBN=9781839531231. In a more fundamental aspect, in [7] we addressed the problem of spacial scaling of general probabilistic policies (e.g. of caching), going beyond Gibbs framework. Also we continued to work on cellular network dimensioning toolbox in a long-term collaboration between TREC/DYOGENE represented by B. Błaszczyszyn, and Orange Labs, represented by M. K. Karray. Furthemore, a collaboration with the Standardization and Research Lab at Nokia Bell Labs and ERC NEMO led by F. Baccelli, started in 2019 and led to several joint publications including [11] New directions started on vehicular networks and particularly on V2X in collaborations with Chang Sik Choi (Hongik University, Korea) and Nithin Ramesan (UT Austin).

3.6 High-dimensional statistical inference and distributed learning

We computed information theoretic bounds for unsupervised and semi-supervised learning and proved complexity bounds for distributed optimization of convex functions using a network of computing units.

3.7 Distributed optimization for machine learning

We obtained new variance reduction results on stochastic Bregman gradient methods [21]. We introduced the "continuized" Nesterov acceleration, a close variant of Nesterov acceleration whose variables are indexed by a continuous time parameter [22], and obtained the first rigorous acceleration of asynchronous gossip algorithms. We also obtained concentration results of non-isotropic random tensors and studied their pplications to learning and empirical risk minimization [23].

3.8 Random Geometry

Point processes and stochastic geometry offer a mathematical framework for the analysis of various random structures and dynamics embedded in Euclidean spaces. In particular, it has enabled efficient analysis of truly deployed wireless networks. Behind this are mathematical asymptotic results (involving growing number of nodes subject to random processes) often leading to ”Poissonisation” of network architectures, and enabling probabilistic analysis. More generally, the analysis of large, homogeneous networks can rely on the key concept of a typical network element (user, base station, link) and its local relationships representing the overall behavior of the network. Indeed, the framework of the stochastic geometry, equipped with Palm calculus for stationary models, and its analog framework for random unimodular graphs, essentially relate to the properties of a typical network element through the so-called ”mass transport” principle. This paradigm was extended beyond the Euclidean case, based on the theory of unimodular networks, see [2]. We developed the probabilistic machinery and also studied applications in a variery of domains: statistical physics, combinatorial optimization, communications, particle gradient descent model for point process generation, processes on Delaunay neighbors in the Poisson-Voronoi tessellation, Dirichlet measures, stochastic games, etc. We collaborated on the matter with V. Anantharam (EECS at UC Berkeley), Ch. Hirsch (University of Groningen), S. Mallat (ENS/Flatiron Institute) and S. Zhang (IRIT-SC).

3.9 Mathematics of stochastic networks via mean-field analysis

In order to understand the fundamental processes taking place in very large networks, it is clear that we sometimes have to abandon the representation of local details and focus on the more macroscopic properties of higher scales. Indeed, the main idea of Mean Field Theory is to replace all detailed body-to-body interactions with a typical element of the network guided by an average or effective interaction. This year, we have several results in this area related to neural networks, opinion dynamics and car-sharing systems.

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 Social and environmental responsibility

6 Highlights of the year

6.1 Awards

- The paper [22] on "A Continuized View on Nesterov Acceleration for Stochastic Gradient Descent and Randomized Gossip" by Mathieu Even, Raphaël Berthier, Francis Bach, Nicolas Flammarion, Pierre Gaillard, Hadrien Hendrikx, Laurent Massoulié and Adrien Taylor received a outstanding paper award at Neurips 2021; cf neurips.cc/virtual/2021/awards_detail.

- Bianca Marin Moreno received a research internship award (section Applied mathematics) from Ecole Polytechnique for her internship entitled "A Stochastic Model and Data Analysis of the Incentive Policy of a Free-Floating Car Sharing System".

- Julien Ancel received congratulations (section Applied mathematics) from Ecole Polytechnique for his research internship entitled "Stochastic modelisation of 2-classes bike-sharing networks".

7 New results

Participants: All Dyogene.

7.1 Models of infectious diseases

1. ***The role of mobility on the propagation of epidemics on point processes*** [4] This paper is focused on SIS (Susceptible-Infected-Susceptible) epidemic dynamics (also known as the contact process) on populations modeled by homogeneous Poisson point processes of the Euclidean plane, where the infection rate of a susceptible individual is proportional to the number of infected individuals in a disc around it. The main focus of the paper is a model where points are also subject to some random motion. Conservation equations for moment measures are leveraged to analyze the stationary regime of the point processes of infected and susceptible individuals. A heuristic factorization of the third moment measure is then proposed to obtain simple polynomial equations allowing one to derive closed form approximations for the fraction of infected individuals in the steady state. These polynomial equations also lead to a phase diagram which tentatively delineates the regions of the space of parameters (population density, infection radius, infection and recovery rate, and motion rate) where the epidemic survives and those where there is extinction. A key take-away from this phase diagram is that the extinction of the epidemic is not always aided by a decrease in the motion rate. These results are substantiated by simulations on large two dimensional tori. These simulations show that the polynomial equations accurately predict the fraction of infected individuals when the epidemic survives. The simulations also show that the proposed phase diagram accurately predicts the parameter regions where the mean survival time of the epidemic increases (resp. decreases) with motion rate.

7.2 Distributed network control and smart-grids

2. ***Kullback-Leibler-Quadratic Optimal Control in a Stochastic Environment*** [19] This work presents advances in Kullback-Leibler-Quadratic (KLQ) optimal control: a stochastic control framework for Markovian models. The motivation is distributed control of large networked systems. The objective function is composed of a control cost in the form of Kullback-Leibler divergence plus a quadratic cost on the sequence of marginal distributions. With this choice of objective function, the optimal probability distribution of a population of agents over a finite time horizon is shown to be an exponential tilting of the nominal probability distribution. The same is true for the controlled transition matrices that induce the optimal probability distribution. However, one limitation of the previous work is that randomness can only be introduced via the control policy; all uncontrolled processes must be modeled as deterministic to render them immutable under an exponential tilting. In this work, only the controlled dynamics are subject to tilting, allowing for more general probabilistic models. Numerical experiments are conducted in the context of power networks. The distributed control techniques described in this paper can transform a large collection of flexible loads into a 'virtual battery' capable of delivering the same grid services as traditional batteries. Additionally, quality of service to the load owner is guaranteed, privacy is preserved, and computation and communication requirements are reduced, relative to alternative centralized control techniques.

3. ***Control oriented modeling of TCLs*** [20] Thermostatically controlled loads (TCLs) have the potential to be a valuable resource for the Balancing Authority (BA) of the future. Examples of TCLs include household appliances such as air conditioners, water heaters, and refrigerators. Since the rated power of each TCL is on the order of kilowatts, to provide meaningful service for the BA, it is necessary to control large collections of TCLs. To perform design of a distributed coordination/control algorithm, the BA requires a control oriented model that describes the relevant dynamics of an ensemble. Works focusing on solely modeling the ensemble date back to the 1980's, while works focusing on control oriented modeling are more recent. In this work, we contribute to the control oriented modeling literature. We leverage techniques from computational fluid dynamics (CFD) to discretize a pair of Fokker-Planck equations derived in earlier work. The discretized equations are shown to admit a certain factorization, which makes the developed model useful for control design. In particular, the effects of weather and control are shown to independently effect the system dynamics.

4. *A unified framework for coordination of thermostatically controlled loads* [35] 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. 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.

5. *A Generalized Nash Equilibrium analysis of the interaction between a peer-to-peer financial market and the distribution grid* [28] We consider the interaction between the distribution grid (physical level) managed by the distribution system operator (DSO), and a financial market in which prosumers optimize their demand, generation, and bilateral trades in order to minimize their costs subject to local constraints and bilateral trading reciprocity coupling constraints. We model the interaction problem between the physical and financial levels as a noncooperative generalized Nash equilibrium problem. We compare two designs of the financial level prosumer market: a centralized design and a peer-to-peer fully distributed design. We prove the Pareto efficiency of the equilibria under homogeneity of the trading cost preferences. In addition, we prove that the pricing structure of our noncooperative game does not permit free-lunch behavior. Finally, in the numerical section we provide additional insights on the efficiency loss with respect to the different levels of agents' flexibility and amount of renewables in the network. We also quantify the impact of the prosumers' pricing on the noncooperative game social cost.

6. *Privacy Impact on Generalized Nash Equilibrium in Peer-to-Peer Electricity Market* [15] We consider a peer-to-peer electricity market, where agents hold private information that they might not want to share. The problem is modeled as a noncooperative communication game, which takes the form of a Generalized Nash Equilibrium Problem, where the agents determine their randomized reports to share with the other market players, while anticipating the form of the peer-to-peer market equilibrium. In the noncooperative game, each agent decides on the deterministic and random parts of the report, such that (a) the distance between the deterministic part of the report and the truthful private information is bounded and (b) the expectation of the privacy loss random variable is bounded. This allows each agent to change her privacy level. We characterize the equilibrium of the game, prove the uniqueness of the Variational Equilibria and provide a closed form expression of the privacy price. In addition, we provide a closed form expression to measure the impact of the privacy preservation caused by inclusion of random noise and deterministic deviation from agents' true values. Numerical illustrations are presented on the 14-bus IEEE network.

7. *A product form for the general stochastic matching model* [12] We consider a stochastic matching model with a general compatibility graph, as introduced by Mairesse and Moyal (2016). We show that the natural necessary condition of stability of the system is also sufficient for the natural 'first-come, first-matched' matching policy. To do so, we derive the stationary distribution under a remarkable product form, by using an original dynamic reversibility property related to that of Adan, Bušić, Mairesse, and Weiss (2018) for the bipartite matching model.

8. *Stochastic dynamic matching: A mixed graph-theory and linear-algebra approach* [36] 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.

9. ***A Multiclass Energy Packet Networks with finite capacity energy queues*** [14] Energy packet Network (EPN) consists of a queueing network formed by blocks, where each of them is formed by one data queue, that handles the workload, and one energy queue, that handles packets of energy. We study an EPN model where the energy packets start the transfer. In this model, energy packets are sent to the data queue of the same block. An energy packet routes one workload packet to the next block if the data queue is not empty, and it is lost otherwise. We assume that the energy queues have a finite buffer size and if an energy packet arrives to the system when the buffer is full, jump-over blocking (JOB) is performed, and therefore with some probability it is sent to the data queue and it is lost otherwise. We first provide a value of the jump-over blocking probability such that the steady-state probability distribution of packets in the queues admits a product form solution. The product form is established for multiserver and multiclass data packet queues under FCFS, preemptive LCFS and PS discipline. Moreover, in the case of a directed tree queueing network, we show that the number of data packets in each subtree decreases as the JOB probability increases for each block.

7.3 Reinforcement learning

10. ***Fundamental Design Principles for Reinforcement Learning Algorithms*** [29] Along with the sharp increase in visibility of the field, the rate at which new reinforcement learning algorithms are being proposed is at a new peak. While the surge in activity is creating excitement and opportunities, there is a gap in understanding of two basic principles that these algorithms need to satisfy for any successful application. One has to do with guarantees for convergence, and the other concerns the convergence rate. The vast majority of reinforcement learning algorithms belong to a class of learning algorithms known as stochastic approximation (SA). The objective here is to review the foundations of reinforcement learning algorithm design based on recent and ancient results from SA. In particular, it was established in (Borkar and Meyn, 2000) that both stability and convergence of these algorithms are guaranteed by analyzing the stability of two associated ODEs. Moreover, if the linearized ODE passes a simple eigenvalue test, then an optimal rate of convergence is guaranteed. This chapter contains a survey of these concepts, along with a survey of the new class of Zap reinforcement learning algorithms introduced by the authors. These algorithms can achieve convergence almost universally, while also guaranteeing optimal rate of convergence.

7.4 Mathematics of wireless cellular networks

11. ***Maximum Utility-Aware Capacity Partitioning in Cooperative Computing*** [16] In many networks, a user has to allocate the link capacity between upload and download. When such networks are used for cooperative computing, the user needs to maintain the division of upload and download capacities at an optimal value to receive the maximum utility. To determine this optimal value, we model upload-download partitioning as a resource maximization game. We show that a Nash equilibrium (NE) obtained for this game is socially optimal. Thus this NE acts as an upper bound on capacity partitioning and serves as a benchmark to analyze the efficiency and performance of various capacity partitioning algorithms. Specifically, using this upper bound and simulations, we examine the performance of different partitioning algorithms while considering the dynamics of resource requests.

12. ***Where to Deploy Reconfigurable Intelligent Surfaces in the Presence of Blockages?*** [27] Wireless communications aided by reconfigurable intelligent surfaces (RISs) is a promising way to improve the coverage for cellular users. The controlled reflection of the signal from RISs is especially useful in mm-wave networks when the direct link between a cellular user and its serving base station (BS) is weak or unavailable due to blockages. But the joint blockage of the user-RIS and the user-BS links may significantly degrade the performance of RIS-aided transmissions. This paper aims to study the effect of joint blockages on downlink performance. When the RIS locations are coupled with BS locations, using tools from stochastic geometry, we obtain an optimal placement of RISs either to minimize the joint blockage probability of the user-RIS and the user-BS links or to maximize the downlink coverage probability. The results show that installing RISs on the street intersections improves the coverage probability. For users associated with BSs that are deployed sufficiently close to intersections, the intersection-mounted RISs offer a better coverage performance compared to BS-coupled RISs.

13. ***Beam Management in Cellular Networks*** [11] Beam management is central in the operation of beamformed wireless cellular systems such as 5G New Radio (NR) networks. Focusing the energy radiated to mobile terminals (MTs) by increasing the number of beams per cell increases signal power and decreases interference, and has hence the potential to bring major improvements on area spectral efficiency (ASE). We proposed a first system-level stochastic geometry model encompassing major aspects of the beam management problem: frequencies, antenna configurations, and propagation; physical layer, wireless links, and coding; network geometry, interference, and resource sharing; sensing, signaling, and mobility management. This model leads to a simple analytical expression for the effective rate that the typical user gets in this context. This in turn allows one to find the number of beams per cell and per MT that maximizes the effective ASE by offering the best tradeoff between beamforming gains and beam management operational overheads and costs, for a wide variety of 5G network scenarios including millimeter wave (mmWave) and sub-6 GHz. As part of the system-level analysis, we define and analyze several underlying new and fundamental performance metrics that are of independent interest. The numerical results discuss the effects of different systemic tradeoffs and performance optimizations of mmWave and sub-6 GHz 5G deployments.

14. ***A Fine-Grained Analysis of Radar Detection in Vehicular Networks*** [26] Automotive radar is a critical feature in advanced driver-assistance systems. It is important in enhancing vehicle safety by detecting the presence of other vehicles in the vicinity. The performance of radar detection is, however, affected by the interference from radars of other vehicles as well as the variation in the target radar cross-section (RCS) due to varying physical features of the target vehicle. Considering such interference and random RCS, this work provides a fine-grained performance analysis of radar detection. Specifically, using stochastic geometry, we calculate the meta distribution of the signal-to-interference-and-noise ratio that permits the reliability analysis of radar detection at individual vehicles. We also evaluate the delay aspect of radar detection, namely, the mean local delay which is the average number of transmission attempts needed until the first successful target detection. For a given target distance, we obtain the optimal transmit probability that maximizes the density of successful radar detection while keeping the mean local delay below a threshold. We also provide several system design insights in terms of the fraction of reliable radar links, transmission delay, the density of vehicles, and congestion control.

15. ***Performance of vehicle-to-everything (V2X) communications*** [8] We analyzed the broadcast of safety-related V2X communications in cellular networks where base stations and vehicles are assumed to share the same spectrum and vehicles broadcast their safety messages to neighboring users. We model the locations of vehicles as a Poisson line Cox point process and the locations of users as a planar Poisson point process. We assume that users are associated with their closest base stations when there is no vehicle within a certain distance ρ. On the other hand, users located within a distance ρ from vehicles are associated with the vehicles to receive their safety messages. We quantify the properties of this vehicle-prioritized association using the stochastic geometry framework. We derive the fractions of users that receive safety messages from vehicles. Then, we obtain the expression for the signal-to-interference ratio of the typical user evaluated on each association type. To address the impact of vehicular broadcast on the cellular network, we also derived the effective rate offered to the typical user in this setting

16. ***Randomised Geographic Caching and its Applications in Wireless Networks*** [30] The randomised (or probabilistic) geographic caching is a proactive content placement strategy that has attracted a lot of attention, because it can simplify a great deal cache-management problems at the wireless edge. It diversifies content placement over caches and applies to scenarios where a request can be possibly served by multiple cache memories. Its simplicity and strength is due to randomisation. It allows one to formulate continuous optimisation problems for content placement over large homogeneous geographic areas. These can be solved to optimality by standard convex methods, and can even provide closed-form solutions for specific cases. This way the algorithmic obstacles from NP-hardness are avoided and optimal solutions can be derived with low computational cost. Randomised caching has a large spectrum of applications in real-world wireless problems, including femto-caching, multi-tier networks, device-to-device communications, mobility, mm-wave, security, UAVs, and more. In this chapter we will formally present the main policy with its applications in various wireless scenarios. We will further introduce some very useful extensions related to unequal file-sizes and content placement with neighbourhood dependence.

17. ***How Wireless Queues Benefit from Motion*** [13] This paper considers the time evolution of a queue that is embedded in a Poisson point process of moving wireless interferers. The queue is driven by an external arrival process and is subject to a time-varying service process that is a function of the SINR that it sees. Static configurations of interferers result in an infinite queue workload with positive probability. In contrast, a generic stability condition is established for the queue in the case where interferers possess any non-zero mobility that results in displacements that are both independent across interferers and oblivious to interferer positions. The proof leverages the mixing property of the Poisson point process. The effect of an increase in mobility on queuing metrics is also studied. Convex ordering tools are used to establish that faster moving interferers result in a queue workload that is smaller for the increasing-convex stochastic order. As a corollary, mean workload and mean delay decrease as network mobility increases. This stochastic ordering as a function of mobility is explained by establishing positive correlations between SINR level-crossing events at different time points, and by determining the autocorrelation function for interference and observing that it decreases with increasing mobility. System behaviour is empirically analyzed using discrete-event simulation and the performance of various mobility models is evaluated using heavy-traffic approximations.

18. ***On Velocity-based Association Policies for Multi-tier 5G Wireless Networks*** [43] Mobility is a key challenge for beam management in 5G cellular networks due to the overhead incurred at beam switching and base station (BS) handover events. This paper focuses on a network that has a multi-tier structure with two types of BSs operating in the same frequency bands, namely macro BSs that are sparser but with higher transmit power, and micro BSs that are denser and with lower transmit power. We propose a downlink user association policy which is a function of the user mobility. Typically, high mobility users should associate with macro BSs so as to incur less beam switching overhead, whereas low mobility ones should be associated with micro BSs. The main contribution of the paper is a formalization of the optimal threshold association policy, when the optimality is understood with respect to the effective Shannon rate. The analysis is based on stochastic geometry and on an exact representation of the effective Shannon rate of the typical user in this beamforming multi-tier context. Two models are discussed. The simplest one focuses on a single-user optimization problem. We also discuss a more realistic model with bandwidth sharing between all users in the cell. Finally, we identify the mobility and user-density patterns where the velocity-based threshold association policy outperforms the classical best mean power association policy.

19. ***Energy and Delay Trade-Offs of End-to-End Vehicular Communications using a Hyperfractal Urban Modelling*** [33] 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 the hyperfractal model which charaterize 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 $\delta > 1$ 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. The results are confirmed through simulations using different fractal dimensions in a Matlab simulator.

7.5 High-dimensional statistical inference

20. ***Emergence of extended states at zero in the spectrum of sparse random graphs*** [9] We confirm the long-standing prediction that $c = e \approx 2.718$ is the threshold for the emergence of a non-vanishing absolutely continuous part (extended states) at zero in the limiting spectrum of the Erdős-Renyi random graph with average degree c. This is achieved by a detailed second-order analysis of the resolvent $(A-z)^{-1}$ near the singular point $z = 0$, where A is the adjacency operator of the Poisson-Galton-Watson tree with mean offspring c. More generally, our method applies to arbitrary unimodular Galton-Watson trees, yielding explicit criteria for the presence or absence of extended states at zero in the limiting spectral measure of a variety of random graph models, in terms of the underlying degree distribution.

21. ***Sparse matrices: convergence of the characteristic polynomial seen from infinity*** [37] We prove that the reverse characteristic polynomial $\det(I_n - zA_n)$ of a random $n \times n$ matrix A_n with iid Bernoulli(d/n) entries converges in distribution towards the random infinite product $\prod_{\ell=1}^{\infty}(1-z^\ell)^{Y_\ell}$ where Y_ℓ are independent Poisson(d^ℓ/ℓ) random variables. We show that this random function is a Poisson analog of more classical Gaussian objects such as the Gaussian holomorphic chaos. As a byproduct, we obtain new simple proofs of previous results on the asymptotic behaviour of extremal eigenvalues of sparse Erdős-Rényi digraphs: for every $d > 1$, the greatest eigenvalue of A_n is close to d and the second greatest is smaller than $\sqrt{d}$, a Ramanujan-like property for irregular digraphs. For $d < 1$, the only non-zero eigenvalues of A_n converge to a Poisson multipoint process on the unit circle. Our results also extend to the semi-sparse regime where d is allowed to grow to ∞ with n, slower than $n^{o(1)}$. We show that the reverse characteristic polynomial converges towards a more classical object written in terms of the exponential of a log-correlated real Gaussian field. In the semi-sparse regime, the empirical spectral distribution of $A_n/\sqrt{d_n}$ converges to the circle distribution; as a consequence of our results, the second eigenvalue sticks to the edge of the circle.

22. ***Expressive Power of Invariant and Equivariant Graph Neural Networks*** [18] Various classes of Graph Neural Networks (GNN) have been proposed and shown to be successful in a wide range of applications with graph structured data. In this paper, we propose a theoretical framework able to compare the expressive power of these GNN architectures. The current universality theorems only apply to intractable classes of GNNs. Here, we prove the first approximation guarantees for practical GNNs, paving the way for a better understanding of their generalization. Our theoretical results are proved for invariant GNNs computing a graph embedding (permutation of the nodes of the input graph does not affect the output) and equivariant GNNs computing an embedding of the nodes (permutation of the input permutes the output). We show that Folklore Graph Neural Networks (FGNN), which are tensor based GNNs augmented with matrix multiplication are the most expressive architectures proposed so far for a given tensor order. We illustrate our results on the Quadratic Assignment Problem (a NP-Hard combinatorial problem) by showing that FGNNs are able to learn how to solve the problem, leading to much better average performances than existing algorithms (based on spectral, SDP or other GNNs architectures). On a practical side, we also implement masked tensors to handle batches of graphs of varying sizes.

23. ***Impossibility of Partial Recovery in the Graph Alignment Problem*** [25] Random graph alignment refers to recovering the underlying vertex correspondence between two random graphs with correlated edges. This can be viewed as an average-case and noisy version of the well-known graph isomorphism problem. For the correlated Erdős-Rényi model, we prove an impossibility result for partial recovery in the sparse regime, with constant average degree and correlation, as well as a general bound on the maximal reachable overlap. Our bound is tight in the noiseless case (the graph isomorphism problem) and we conjecture that it is still tight with noise. Our proof technique relies on a careful application of the probabilistic method to build automorphisms between tree components of a subcritical Erdős-Rényi graph.

24. ***Sharp threshold for alignment of graph databases with Gaussian weights*** [24] We study the fundamental limits for reconstruction in weighted graph (or matrix) database alignment. We consider a model of two graphs where π^* is a planted uniform permutation and all pairs of edge weights $(A_{i,j}, B_{\pi^*(i),\pi^*(j)})_{1\le i<j\le n}$ are i.i.d. pairs of Gaussian variables with zero mean, unit variance and correlation parameter $\rho \in [0,1]$. We prove that there is a sharp threshold for exact recovery of π^*: if $n\rho^2 \ge (4+\epsilon)\log n + \omega(1)$ for some $\epsilon > 0$, there is an estimator $\hat{\pi}$ – namely the MAP estimator – based on the observation of databases A, B that achieves exact reconstruction with high probability. Conversely, if $n\rho^2 \le 4\log n - \log\log n - \omega(1)$, then any estimator $\hat{\pi}$ verifies $\hat{\pi} = \pi$ with probability $o(1)$. This result shows that the information-theoretic threshold for exact recovery is the same as the one obtained for detection in a recent work by Wu et al. (2020): in other words, for Gaussian weighted graph alignment, the problem of reconstruction is not more difficult than that of detection. Though the reconstruction task was already well understood for vector-shaped database alignment (that is taking signal of the form $(u_i, v_{\pi^*(i)})_{1\le i\le n}$ where $(u_i, v_{\pi^*(i)})$ are i.i.d. pairs in $\mathbb{R}^{d_u} \times \mathbb{R}^{d_v}$), its formulation for graph (or matrix) databases brings a drastically different problem for which the hard phase is conjectured to be wide. The proofs build upon the analysis of the MAP estimator and the second moment method, together with the study of the correlation structure of energies of permutations.

25. ***A simpler spectral approach for clustering in directed network*** [38] We study the task of clustering in directed networks. We show that using the eigenvalue/eigenvector decomposition of the adjacency matrix is simpler than all common methods which are based on a combination of data regularization and SVD truncation, and works very well down to the very sparse regime where the edge density has constant order. This simple approach was largely unnoticed in the mathematics and network science communities. Our analysis is based on a Master Theorem describing sharp asymptotics for isolated eigenvalues/eigenvectors of sparse, non-symmetric matrices with independent entries. We also describe the limiting distribution of the entries of these eigenvectors; in the task of digraph clustering with spectral embeddings, we provide numerical evidence for the superiority of Gaussian Mixture clustering over the widely used k-means algorithm.

26. ***Accelerating Abelian Random Walks with Hyperbolic Dynamics*** [39] Given integers $d \ge 2, n \ge 1$, we consider affine random walks on torii $(\mathbb{Z}/n\mathbb{Z})^d$ defined as $X_{t+1} = AX_t + B_t \bmod n$, where $A \in \mathrm{GL}_d(\mathbb{Z})$ is an invertible matrix with integer entries and $(B_t)_{t\ge 0}$ is a sequence of iid random increments on $\mathbb{Z}^d$. We show that when A has no eigenvalues of modulus 1, this random walk mixes in $O(\log n \log\log n)$ steps as $n \to \infty$, and mixes actually in $O(\log n)$ steps only for almost all n. These results generalize those on the so-called Chung-Diaconis-Graham process, which corresponds to the case $d = 1$. Our proof is based on the initial arguments of Chung, Diaconis and Graham, and relies extensively on the properties of the dynamical system $x \mapsto A^\top x$ on the continuous torus $\mathbb{R}^d/\mathbb{Z}^d$. Having no eigenvalue of modulus one makes this dynamical system a hyperbolic toral automorphism, a typical example of a chaotic system known to have a rich behaviour. As such our proof sheds new light on the speed-up gained by applying a deterministic map to a Markov chain.

27. ***Asynchrony and Acceleration in Gossip Algorithms*** [41] This paper considers the minimization of a sum of smooth and strongly convex functions dispatched over the nodes of a communication network. Previous works on the subject either focus on synchronous algorithms, which can be heavily slowed down by a few slow nodes (the straggler problem), or consider a historical asynchronous setting (Boyd et al., 2006), which relies on a communication model that cannot be readily implemented in practice, as it does not capture important aspects of asynchronous communications such as non-instantaneous computations and communications. We have two main contributions. 1) We introduce a new communication scheme, based on Loss-Networks, that is programmable in a fully asynchronous and decentralized fashion. We establish empirically and theoretically that it improves over existing synchronous algorithms by depending on local communication delays in the analysis instead of global worst-ones. 2) We provide an acceleration of the standard gossip algorithm in the historical asynchronous model without requiring any additional synchronization.

28. ***Non-backtracking spectra of weighted inhomogeneous random graphs*** [44] We study a model of random graphs where each edge is drawn independently (but not necessarily identically distributed) from the others, and then assigned a random weight. When the mean degree of such a graph is low, it is known that the spectrum of the adjacency matrix A deviates significantly from that of its expected value $\mathbb{E}A$. In contrast, we show that over a wide range of parameters the top eigenvalues of the non-backtracking matrix B – a matrix whose powers count the non-backtracking walks between two edges – are close to those of $\mathbb{E}A$, and all other eigenvalues are confined in a bulk with known radius. We also obtain a precise characterization of the scalar product between the eigenvectors of B and their deterministic counterparts derived from the model parameters. This result has many applications, in domains ranging from (noisy) matrix completion to community detection, as well as matrix perturbation theory. In particular, we establish as a corollary that a result known as the Baik-Ben Arous-Péché phase transition, previously established only for rotationally invariant random matrices, holds more generally for matrices A as above under a mild concentration hypothesis.

7.6 Distributed optimization for machine learning

29. ***Fast Stochastic Bregman Gradient Methods: Sharp Analysis and Variance Reduction*** [21] We study the problem of minimizing a relatively-smooth convex function using stochastic Bregman gradient methods. We first prove the convergence of Bregman Stochastic Gradient Descent (BSGD) to a region that depends on the noise (magnitude of the gradients) at the optimum. In particular, BSGD with a constant step-size converges to the exact minimizer when this noise is zero (*interpolation* setting, in which the data is fit perfectly). Otherwise, when the objective has a finite sum structure, we show that variance reduction can be used to counter the effect of noise. In particular, fast convergence to the exact minimizer can be obtained under additional regularity assumptions on the Bregman reference function. We illustrate the effectiveness of our approach on two key applications of relative smoothness: tomographic reconstruction with Poisson noise and statistical preconditioning for distributed optimization.

30. ***A Continuized View on Nesterov Acceleration for Stochastic Gradient Descent and Randomized Gossip*** [22] We introduce the "continuized" Nesterov acceleration, a close variant of Nesterov acceleration whose variables are indexed by a continuous time parameter. The two variables continuously mix following a linear ordinary differential equation and take gradient steps at random times. This continuized variant benefits from the best of the continuous and the discrete frameworks: as a continuous process, one can use differential calculus to analyze convergence and obtain analytical expressions for the parameters; and a discretization of the continuized process can be computed exactly with convergence rates similar to those of Nesterov original acceleration. We show that the discretization has the same structure as Nesterov acceleration, but with random parameters. We provide continuized Nesterov acceleration under deterministic as well as stochastic gradients, with either additive or multiplicative noise. Finally, using our continuized framework and expressing the gossip averaging problem as the stochastic minimization of a certain energy function, we provide the first rigorous acceleration of asynchronous gossip algorithms.

31. ***Concentration of Non-Isotropic Random Tensors with Applications to Learning and Empirical Risk Minimization*** [23] Dimension is an inherent bottleneck to some modern learning tasks, where optimization methods suffer from the size of the data. In this paper, we study non-isotropic distributions of data and develop tools that aim at reducing these dimensional costs by a dependency on an effective dimension rather than the ambient one. Based on non-asymptotic estimates of the metric entropy of ellipsoids-that prove to generalize to infinite dimensions-and on a chaining argument, our uniform concentration bounds involve an effective dimension instead of the global dimension, improving over existing results. We show the importance of taking advantage of non-isotropic properties in learning problems with the following applications: i) we improve state-of-the-art results in statistical preconditioning for communication-efficient distributed optimization, ii) we introduce a non-isotropic randomized smoothing for nonsmooth optimization. Both applications cover a class of functions that encompasses empirical risk minization (ERM) for linear models.

7.7 Stochastic Geometry

32. ***Optimal stationary markings*** [7] Many specific problems ranging from theoretical probability to applications in statistical physics, combinatorial optimization and communications can be formulated as an optimal tuning of local parameters in large systems of interacting particles. Using the framework of stationary point processes in the Euclidean space, we pose it as a problem of an optimal stationary marking of a given stationary point process. The quality of a given marking is evaluated in terms of scores calculated in a covariant manner for all points in function of the proposed marked configuration. In the absence of total order of the configurations of scores, we identify intensity-optimality and local optimality as two natural ways for defining optimal stationary marking. We derive tightness and integrability conditions under which intensity-optimal markings exist and further stabilization conditions making them equivalent to locally optimal ones. We present examples motivating the proposed, general framework. Finally, we discuss various possible approaches leading to uniqueness results.

33. ***Continuum Line-of-Sight Percolation on Poisson-Voronoi Tessellations*** [10] In this work, we study a new model for continuum line-of-sight percolation in a random environment given by a Poisson-Voronoi tessellation. The edges of this tessellation are the support of a Cox point process, while the vertices are the support of a Bernoulli point process. Taking the superposition $\mathbb{Z}$ of these two processes, two points of $\mathbb{Z}$ are linked by an edge if and only if they are sufficiently close and located on the same edge of the supporting tessellation. We study the percolation of the random graph arising from this construction and prove that a subcritical phase as well as a supercritical phase exist under general assumptions. Our proofs are based on a renormalization argument with some notion of stabilization and asymptotic essential connectedness to investigate continuum percolation for Cox point processes. We also give numerical estimates of the critical parameters of the model. Our model can be seen as a good candidate for modelling telecommunications networks in a random environment with obstructive conditions for signal propagation.

34. ***On Point Processes Defined by Angular Conditions on Delaunay Neighbors in the Poisson-Voronoi Tessellation*** [3] Consider a homogeneous Poisson point process of the Euclidean plane and its Voronoi tessellation. The present note discusses the properties of two stationary point processes associated with the latter and depending on a parameter θ. The first one is the set of points that belong to some one-dimensional facet of the Voronoi tessellation and are such that the angle with which they see the two nuclei defining the facet is θ. The main question of interest on this first point process is its intensity. The second point process is that of the intersections of the said tessellation with a straight line having a random orientation. Its intensity is well known. The intersection points almost surely belong to one-dimensional facets. The main question here is about the Palm distribution of the angle with which the points of this second point process see the two nuclei associated with the facet. The note gives answers to these two questions and briefly discusses their practical motivations. It also discusses natural extensions to dimension three.

35. ***Unimodular Hausdorff and Minkowski dimensions*** [2] We introduced two new notions of dimension, namely the *unimodular Minkowski and Hausdorff dimensions*, which are inspired from the classical analogous notions. These dimensions are defined for *unimodular discrete spaces*, introduced in this work, which provide a common generalization to stationary point processes under their Palm version and unimodular random rooted graphs. The use of unimodularity in the definitions of dimension is novel. Also, a toolbox of results was presented for the analysis of these dimensions. In particular, analogues of Billingsley's lemma and Frostman's lemma are presented. These last lemmas are instrumental in deriving upper bounds on dimensions, whereas lower bounds are obtained from specific coverings. The notions of unimodular Hausdorff size, which is a discrete analogue of the Hausdorff measure, and unimodular dimension function are also introduced. This toolbox allows one to connect the unimodular dimensions to other notions such as volume growth rate, discrete dimension and scaling limits. It is also used to analyze the dimensions of a set of examples pertaining to point processes, branching processes, random graphs, random walks, and self-similar discrete random spaces. Further results of independent interest are also presented, like a version of the max-flow min-cut theorem for unimodular one-ended trees and a weak form of pointwise ergodic theorems for all unimodular discrete spaces.

7.8 Mathematics of stochastic networks via mean-field analysis

36. ***Pair Replica Mean-Field Neural Networks*** [5] Replica-mean-field models have been proposed to decipher the activity of otherwise analytically intractable neural networks via a multiply-and-conquer approach. In this approach, one considers limit networks made of infinitely many replicas with the same basic neural structure as that of the network of interest, but exchanging spikes in a randomized manner. The key point is that these replica-mean-field networks are tractable versions that retain important features of the finite structure of interest. To date, the replica framework has been discussed for first-order models, whereby elementary replica constituents are single neurons with independent Poisson inputs. In [5], we extend this replica framework to allow elementary replica constituents to be composite objects, namely, pairs of neurons. As they include pairwise interactions, these pair-replica models exhibit nontrivial dependencies in their stationary dynamics, which cannot be captured by first-order replica models. Our contributions are two-fold: (i) We analytically characterize the stationary dynamics of a pair of intensity-based neurons with independent Poisson input. This analysis involves the reduction of a boundary-value problem related to a two-dimensional transport equation to a system of Fredholm integral equations—a result of independent interest. (ii) We analyze the set of consistency equations determining the full network dynamics of certain replica limits. These limits are those for which replica constituents, be they single neurons or pairs of neurons, form a partition of the network of interest. Both analyses are numerically validated by computing input/output transfer functions for neuronal pairs and by computing the correlation structure of certain pair-dominated network dynamics.

37. ***Replica-mean-field limits of fragmentation-interaction-aggregation processes*** [1] Network dynamics with point-process-based interactions are of paramount modeling interest. Unfortunately, most relevant dynamics involve complex graphs of interactions for which an exact computational treatment is impossible. To circumvent this difficulty, the replica-mean-field approach focuses on randomly interacting replicas of the networks of interest. In the limit of an infinite number of replicas, these networks become analytically tractable under the so-called 'Poisson hypothesis'. However, in most applications this hypothesis is only conjectured. In this paper we establish the Poisson hypothesis for a general class of discrete-time, point-process-based dynamics that we propose to call fragmentation-interaction-aggregation processes, and which are introduced here. These processes feature a network of nodes, each endowed with a state governing their random activation. Each activation triggers the fragmentation of the activated node state and the transmission of interaction signals to downstream nodes. In turn, the signals received by nodes are aggregated to their state. Our main contribution is a proof of the Poisson hypothesis for the replica-mean-field version of any network in this class. The proof is obtained by establishing the propagation of asymptotic independence for state variables in the limit of an infinite number of replicas. Discrete-time Galves–Löcherbach neural networks are used as a basic instance and illustration of our analysis.

38. ***Opinion Dynamics*** [6] We introduced a non-linear and continuous-time opinion dynamics model with additive noise and state-dependent interaction rates between agents. The model features interaction rates which are proportional to a negative power of the opinion distances. We establish a non-local partial differential equation for the distribution of opinion distances and use Mellin transforms to provide an explicit formula for the stationary solution of the latter, when it exists. Our approach leads to new qualitative and quantitative results on this type of dynamics. To the best of our knowledge these Mellin transform results are the first quantitative results on the equilibria of opinion dynamics with distance-dependent interaction rates. The closed-form expressions for this class of dynamics are obtained for the two-agent case. However, the results can be used in mean-field models featuring several agents whose interaction rates depend on the empirical average of their opinions. The technique also applies to linear dynamics, namely with a constant interaction rate, on an interaction graph.

39. ***Stochastic Modelling of Free-Floating Car-Sharing Systems*** [40] Car-sharing systems (CSSs) have gained popularity during the last decade as a flexible, efficient and ecological alternative mode of transportation. But for the operator, managing such systems is far to be simple. Due to heterogeneity of demand and also randomness, the user may face a lack of resources: no car or no parking space available. And the operator has to design the system in order to improve it. The total number of cars impact the performance of the system. We address the dimensioning issue. For that, mathematical models are needed. In many cities, two systems coexist: station-based and free-floating. The latter gives more flexibility to the user both to take or return the car. But he can reserve only the car for a short period, and not the parking space, as the car is parked on public space with no specific parking spaces. The car reservation is here to help the user. The aim of the paper is to study its influence on the system behavior. This study focuses on Communauto's Montreal free-floating car-sharing system (FFCSS). Data analysis investigates the main features of the system based on user preferences. It allows proposing a mathematical modelling. Then we present two analytical approaches. First the mean-field method could be used for different variants, and w gives first insights on the optimal fleet size in a homogeneous framework. Second the general inhomogeneous model is described as a closed Jackson network with blocking-rerouting policy. We prove that its state at stationarity is given by a product-form distribution. It allows in future work to obtain an explicit large-scale representation of the system which can be used both theoretically or numerically for optimization purposes.

40. ***Mean field analysis for bike and e-bike sharing systems*** [17] Abstract : Electric bikes are deployed massively in preexisting bike sharing system in order to attract new users and replace cars on a larger scale (see [2]). But this causes interactions between the two populations of bikes. In this paper, we analyze a model of an homogeneous bike sharing system where two classes of bikes interact only through the finite capacity of stations. It models systems with both electric and normal bikes, these classes requiring different subscriptions. As far as we know (see [7]), it is the first stochastic large-scale analysis for integrated e-bike and bike sharing systems. The aim of the paper is to derive explicitly the limiting stationary distribution of the state of a station when the number of stations and the fleet size of each class increase at the same rate. Analysis for a spatially heterogeneous network is in preparation and discussed in Section 4.

41. ***Mean field analysis of stochastic networks with reservation*** [34] The problem of reservation in a large distributed system is analyzed via a new mathematical model. A typical application is a station-based car-sharing system which 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 behavior of the underlying stochastic network is given when the number N of stations and the fleet size 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.

42. ***Mean field analysis of an incentive algorithm for a closed stochastic network*** [42] 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 much long in the low-demand zone, users are encouraged to pick up them 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 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.

8 Bilateral contracts and grants with industry

8.1 Bilateral contracts with industry

Participants: Bartłomiej Błaszczyszyn, Ana Bušić, Antoine Brochard.

8.1.1 Contract with EDF

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

8.1.2 CIFRE with Huawei Technologies France

Contract with Huawei Technologies France started in 2018 and finished in 2021 for the co-advising by B. Błaszczyszyn of a PhD student Antoine Brochard. The PhD has been extended by Inria, who have hired the student until February 2022.

9 Partnerships and cooperations

9.1 ERC NEMO

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Bharath Roy Choudhury, Simon Coste, Ke Feng, Sanket Kalamkar, Sayeh Khaniha, Ali Khezeli, Pierre Popineau.

NEMO, NEtwork MOtion cordis.europa.eu/project/id/788851, project.inria.fr/ercnemo 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 will leverage interactions of Inria with Ecole Normale Supérieure on the mathematical side, and with Nokia Bell Labs and Orange on the engineering side. This year we hired post-doc Ke Feng.

9.2 International initiatives

9.2.1 GSSPP-IFCAM

Participants: Bartłomiej Błaszczyszyn.

Title: Geometric statistics of stationary point processes

Duration: 2018 -> 2021

Coordinator: B. Błaszczyszyn (Inria), Yogeshwaran D. (ISI Bangalore)

Description: Indo-French Centre for Applied Mathematics (IFCAM)

Scientific perimeter of the project

- De-correlation concept for general marked point processes — essential element of limit theory.
- Central Limit Theorems for general dependent interacting particle systems.
- Examples: sequential adsorption, ballistic deposition, majority dynamics, epidemic models — allowing for non-Poisson locations of particles and their dependent initial states.
- Variance asymptotic required for CLTs: volume-order under quasi-local perturbations and other asymptotic for various test statistics.

- Optimization of large particle systems: intensity-optimal and locally optimal, with applications in statistical physics, combinatorial optimization and communications.

9.2.2 RMF

Participants: François Baccelli.

Title: Replica Mean Fields for Networks

Duration: 2021 ->

Coordinator: Senya Shlosman ("Senya" <shlosman@gmail.com>;)

Partners:

- Skoltech

Inria contact: Francois Baccelli

Summary:

9.3 International research visitors

9.3.1 Visits of international scientists

Inria International Chair

IIC- MEYN Sean

Name of the chair: *Sean Meyn*

Institution of origin: *University of Florida*

Country: *Unites States*

Dates: From Tue Jan 01 2019 to Sun Dec 31 2023

Title: Distributed Control and Smart Grid

Summary: Prof. Meyn was at Inria Paris June - July 2021.

9.4 National initiatives

9.4.1 GdR GeoSto

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

9.4.2 GdR RO

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

9.4.3 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.

10 Dissemination

Participants: All Dyogene.

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

In 2021, A. Khezeli organized the weekly DYOGENE seminar. B. Roy-Chowdhury organized the NEMO reading group:

- January 22, 2021: "Uniqueness of stationary fixed point for certain exponential server nodes" by Michel Davydov, INRIA.
- March 26, 2021: "Local weak convergence of networks and graph spectra" by Simon Coste, INRIA.
- April 23, 2021: "Unimodular Hausdorff and Minkowski dimension for unimodular random discrete metric spaces, I " by Ali Khezeli, INRIA.
- May 7, 2021: "Unimodular Hausdorff and Minkowski dimension for unimodular random discrete metric spaces, II" by Ali Khezeli, INRIA.
- June 18, 2021: "Free point processes on unimodular second countable groups weakly factor onto Poisson point processes" by Roman Gambelin, INRIA.
- July 2, 2021: "Unimodular Hausdorff and Minkowski dimension for unimodular random discrete metric spaces, III" by Ali Khezeli, INRIA.
- September 30, 2021: "An introduction to the Aldous diffusion conjecture and algebraic measure trees" by Roman Gambelin, INRIA.
- October 14, 2021: " Shift coupling and Embeddings in Brownian motion" by Hermann Thorisson, University of Iceland.
- December 2, 2021: "The k-parent spatial Λ-Fleming Viot process: construction and limit as k tends to $+\infty$" by Apolline Louvet from MAP5, Université de Paris.

10.1.2 Invited talks

- F. Baccelli:
  - Invited lecture at the Hausdorff Institute on High Dimensional Stochastic Geometry www.him.uni-bonn.de/programs/future-programs/future-trimester-programs/interplay-high-dimensional-geometry-probability/workshop-high-dimensional-spatial-random-systems-february-22-26-2021
  - Colloquium lecture at Georgia Tech, Department of Operations Research on replica mean-field limits for neural networks, March 16, 2021.
  - Invited lecture at IPIT, Moscow on replica mean-field limits for neural networks, June 1, 2021.
  - Invited lecture at the University of Melbourne, Department of Mathematics, on replica mean-field limits for neural networks, June 10, 2021.
  - Keynote lecture at QEST, on Dynamics of Wireless Networks, Paris, August 25. 2021.
- M. Davydov: presentations on mean field limits at
  - Forum des Jeunes Mathématiciennes et Mathématiciens (December 2021, Besançon).
  - Stochastic Geometry Days 2021 (November 2021, Dunkerque, France).
  - Congrès des Jeunes Chercheurs en Mathématiques Appliquées (October 2021, Palaiseau).
  - Journées des Probabilités 2021 (June 2021, Guidel).
  - PHD students seminar of Institut Mathématique de Toulouse (December 2021, Toulouse).
  - Working group in probability, ergodic theory and dynamical systems (November 2021, Rouen).
- S. Khaniha:
  - Stochastic Geometry Days, Dunkerque, November 15th-19th, 2021. Title: Dynamical systems on the null recurrent Doeblin Graph.
  - Forum des Jeunes mathématicien.ne.s (probabilités, statistique et applications), December 8th-10th, 2021, Title: The Doeblin Graph of a null recurrent MC.
- A. Khezeli:
  - 22nd Applied Stochastic Processes Workshop, Alzahra University, Iran, February 2021. Title: Invariant Circle Packings.
  - 8th Conference of Frontiers in Mathematical Sciences, IPM, Iran, April 2021. Title: The Gromov-Hausdorff metric and its generalizations.
  - DYOGENE reading group, minicourse on unimodular dimensions (3 lectures) April 2021, Title: Unimodular Minkowski and Hausdorff dimensions.
  - Combinatorics & Computing Seminars, IPM, Iran, June 2021, Title: Invariant Circle Packing
  - DYOGENE seminar, October 2021, title: Stationary and Point-Stationary Circle Packings.
- M.Lelarge:
  - invited talk at Toutelia 2021: statistical physics, probability and AI indico.math.cnrs.fr/event/6757/
- P. Popineau
  - Presentation at IEEE Globecom 2021, Madrid [43], Dec. 2021.
  - Séminaire du LINCS : On Velocity-based Association Policies for Multi-tier 5G Wireless Networks - 20/10/2021.

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

- Licence: B. Błaszczyszyn (Cours) Théorie de l'information et du codage 24 heqTD, L3, ENS Paris.
- Licence: A. Busic (Cours) and K. Scaman (Cours + TD) Structures et algorithmes aléatoires 60 heqTD, L3, ENS Paris.
- Licence: L. Massoulié (Cours) Social and Communication networks 60 heqTD, L3, l'X.
- Master: A. Busic (Cours) and M. Even (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, M1, ENS Paris, X, X-HEC. mlelarge.github.io/dataflowr-web/
- Master: L. Massoulié (Cours) Inference in large random graphs, M2 Université d'Orsay.
- Master: R. Gambelin, Chargé de TD "Méthodes quantitatives", L2 Eco & Gestion, l'université Paris Descartes;
- Préparation à l'agrégation: S. Coste (Cours+TD) Cours de statistiques, agrégation de sciences sociales, ENS Paris-Saclay.
- MPSI: S. Coste (Interrogations) maths.
- Prépa: R. Gambelin, Colleur, ECG 1ère année au lycée Saint Louis de Gonzague (Franklin).
- Lectures on unimodularity by F. Baccelli at the Stochastic Geometry days, Dunkerque, Nov. 2021.

10.2.2 Supervision

PhD defended:

- Arnaud Cadas, *Stochastic matching models and their applications to demand-supply balancing*, Nov 2021, supervised by A. Bušić; www.theses.fr/s188918
- Hadrien Hendrikx, *Accelerated methods for distributed optimization* [31], Sep 2021, supervised by Laurent Massoulié; www.theses.fr/s209409
- Ludovic Stephan, *Community detection by the block stochastic model* Oct 2021, 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
- Antoine Brochard since Sep 2018, supervised by B. Błaszczyszyn
- Bharath Roy Choudhury since Sep 2019, supervised by F. Baccelli
- Eric Daoud since Sep 2021, supervised by M. Lelarge
- Michel Davydov, since 2020, supervised by F. Baccelli
- Bastien Dubail since Sep 2020, 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
- Sayeh Khaniha, since Feb 2019, supervised by F. Baccelli
- Thomas Le Corre since Nov 2021, supervised by Bušić
- Maxime Leiber since Feb 2020, supervised by Laurent Massoulié
- Pierre Popineau, since Sep 2019, supervised by F. Baccelli
- David Robin, since Oct 2021, supervised by Laurent Massoulié
- Sébastien Samain since Nov 2016, supervised by A. Bušić
- Ilia Shilov since Sep 2019, supervised by A. Bušić
- Amaury Triboulin since Sep 2021, supervised by M. Lelarge
- Lucas Weber since Oct 2021, supervised by A. Bušić

10.2.3 Juries

- Marc Lelarge: jury CRCN INRIA Paris; jury prof. UFR Informatique - Université de Paris; member of the PhD committee for Louis Martin; Reviewer of the PhD thesis for Amine Echraib.
- B. Błaszczyszyn: jury M2 defense Sofia Robert.
- F. Baccelli: member of the thesis committee of D. Anada, INRIA Lyon, October 2021.

10.3 Popularization

10.3.1 Internal or external Inria responsibilities

Les réseaux de communications à l'INRIA. Rapport établi par F. Baccelli, I. Chrisment, J.M. Gorce et P. Mussi à la demande de B. Sportisse. Novembre 2021.

10.3.2 Articles and contents

Rapport de l'académie des sciences sur les réseaux de communications du futur, établi par S. Abiteboul, D. Andler, F. Baccelli, C. Bréchignac, G. Berry, S. Candel, M. Fink et E. Moulines, juillet 2021.

11 Scientific production

11.1 Publications of the year

International journals

[1] F. Baccelli, M. Davydov and T. Taillefumier. 'Replica-mean-field limits of fragmentation-interaction-aggregation processes'. In: *Journal of Applied Probability* (17th Jan. 2022), pp. 1–22. DOI: 10.1017/jpr.2021.31. URL: https://hal.archives-ouvertes.fr/hal-03542535.

[2] F. Baccelli, M.-O. Haji-Mirsadeghi and A. Khezeli. 'Unimodular Hausdorff and Minkowski dimensions'. In: *Electronic Journal of Probability* 26.none (1st Jan. 2021). DOI: 10.1214/21-EJP692. URL: https://hal.archives-ouvertes.fr/hal-03541955.

[3] F. Baccelli and S. Kalamkar. 'On point processes defined by angular conditions on Delaunay neighbors in the Poisson–Voronoi Tessellation'. In: *Journal of Applied Probability* 58.4 (Dec. 2021), pp. 952–965. DOI: 10.1017/jpr.2021.26. URL: https://hal.archives-ouvertes.fr/hal-03542143.

[4] F. Baccelli and N. Ramesan. 'A computational framework for evaluating the role of mobility on the propagation of epidemics on point processes'. In: *Journal of Mathematical Biology* 84.1-2 (Jan. 2022), p. 4. DOI: 10.1007/s00285-021-01692-1. URL: https://hal.archives-ouvertes.fr/hal-03542621.

[5] F. Baccelli and T. Taillefumier. 'The Pair-Replica-Mean-Field Limit for Intensity-based Neural Networks'. In: *SIAM Journal on Applied Dynamical Systems* 20.1 (Jan. 2021), pp. 165–207. DOI: 10.1137/20M1331664. URL: https://hal.archives-ouvertes.fr/hal-03542148.

[6] F. Baccelli, S. Vishwanath and J. Oh Woo. 'On the steady state of continuous-time stochastic opinion dynamics with power-law confidence'. In: *Journal of Applied Probability* 58.3 (Sept. 2021), pp. 746–772. DOI: 10.1017/jpr.2020.113. URL: https://hal.archives-ouvertes.fr/hal-03542120.

[7] B. Błaszczyszyn and C. Hirsch. 'Optimal stationary markings'. In: *Stochastic Processes and their Applications* 138 (Aug. 2021), pp. 153–185. DOI: 10.1016/j.spa.2021.04.003. URL: https://hal.inria.fr/hal-02457091.

[8] C.-S. Choi and F. Baccelli. 'Modeling and Analysis of Vehicle Safety Message Broadcast in Cellular Networks'. In: *IEEE Transactions on Wireless Communications* 20.7 (July 2021), pp. 4087–4099. DOI: 10.1109/TWC.2021.3055837. URL: https://hal.archives-ouvertes.fr/hal-03542182.

[9] S. Coste and J. Salez. 'Emergence of extended states at zero in the spectrum of sparse random graphs'. In: *Annals of Probability* 49.4 (1st May 2021). DOI: 10.1214/20-AOP1499. URL: https://hal.archives-ouvertes.fr/hal-03354274.

[10] Q. L. Gall, B. Błaszczyszyn, E. Cali and T. En-Najjary. 'Continuum Line-of-Sight Percolation on Poisson-Voronoi Tessellations'. In: *Advances in Applied Probability* 53.2 (June 2021), pp. 510–536. DOI: 10.1017/apr.2020.69. URL: https://hal.inria.fr/hal-02192469.

[11] S. Kalamkar, F. Baccelli, F. Abinader, A. Marcano Fani and L. Uzeda Garcia. 'Beam Management in 5G: A Stochastic Geometry Analysis'. In: *IEEE Transactions on Wireless Communications* (20th Sept. 2021). DOI: 10.1109/TWC.2021.3110785. URL: https://hal.archives-ouvertes.fr/hal-03542024.

[12] P. Moyal, A. Bušić and J. Mairesse. 'A product form for the general stochastic matching model'. In: *Journal of Applied Probability* 58.2 (June 2021), pp. 449–468. DOI: 10.1017/jpr.2020.100. URL: https://hal.archives-ouvertes.fr/hal-03294756.

[13] N. Ramesan and F. Baccelli. 'How Wireless Queues Benefit from Motion: An Analysis of the Continuum Between Zero and Infinite Mobility'. In: *IEEE Transactions on Wireless Communications* 20.12 (Dec. 2021), pp. 8149–8162. DOI: 10.1109/TWC.2021.3090762. URL: https://hal.archives-ouvertes.fr/hal-03542203.

[14] S. Samain, J. Doncel, A. Bušić and J.-M. Fourneau. 'Multiclass Energy Packet Networks with finite capacity energy queues'. In: *Performance Evaluation* 152 (Dec. 2021), p. 102228. DOI: 10.1016/j.peva.2021.102228. URL: https://hal.archives-ouvertes.fr/hal-03541754.

[15] I. Shilov, H. Le Cadre and A. Bušić. 'Privacy Impact on Generalized Nash Equilibrium in Peer-to-Peer Electricity Market'. In: *Operations Research Letters* 49 (Sept. 2021), pp. 759–766. URL: https://hal.inria.fr/hal-03112775.

[16] N. Singha, S. Kalamkar and Y. N. Singh. 'Maximum Utility-Aware Capacity Partitioning in Cooperative Computing'. In: *IEEE Communications Letters* 25.10 (Oct. 2021), pp. 3360–3364. DOI: 10.1109/LCOMM.2021.3097045. URL: https://hal.inria.fr/hal-03550073.

International peer-reviewed conferences

[17] J. Ancel, C. Fricker and H. Mohamed. 'Mean field analysis for bike and e-bike sharing systems'. In: MAMA - ACM SIGMETRICS 2021 Workshop on MAthematical performance Modeling and Analysis. Vol. 49. 2. Beijing, China, 17th Jan. 2022, pp. 12–14. DOI: 10.1145/3512798.3512804. URL: https://hal.archives-ouvertes.fr/hal-03539265.

[18] W. Azizian and M. Lelarge. 'Expressive Power of Invariant and Equivariant Graph Neural Networks'. In: ICLR 2021 - International Conference on Learning Representations. Virtual, Unknown Region, 3rd May 2021. URL: https://hal.inria.fr/hal-03464024.

[19] N. Cammardella, A. Bušić and S. Meyn. 'Kullback-Leibler-Quadratic Optimal Control in a Stochastic Environment'. In: *Proceedings of The 60th IEEE conference on Decision and Control*. CDC 2021 - 60th IEEE conference on Decision and Control. Austin (online), United States, 2021. URL: https://hal.archives-ouvertes.fr/hal-03541774.

[20] A. R. Coffman, A. Bušić and P. Barooah. 'Control oriented modeling of TCLs'. In: *Proceedings of the 2021 American Control Conference (ACC)*. 2021 American Control Conference (ACC). New Orleans, United States, 2021. URL: https://hal.archives-ouvertes.fr/hal-03095248.

[21] R.-A. Dragomir, H. Hendrikx and M. Even. 'Fast Stochastic Bregman Gradient Methods: Sharp Analysis and Variance Reduction'. In: ICML 2021- 38th International Conference on Machine Learning. Vol. 139. Proceedings of the 38th International Conference on Machine Learning. virtual, United States, 1st July 2021, pp. 2815–2825. URL: https://hal.archives-ouvertes.fr/hal-03383164.

[22] M. Even, R. Berthier, F. Bach, N. Flammarion, P. Gaillard, H. Hendrikx, L. Massoulié and A. Taylor. 'A Continuized View on Nesterov Acceleration for Stochastic Gradient Descent and Randomized Gossip'. In: *Advances in Neural Information Processing Systems 34*. NeurIPS 2021 - 35th Conference on Neural Information Processing Systems. Sydney (virtual), Australia: Morgan Kaufmann Publishers, 1st Dec. 2021, pp. 1–32. URL: https://hal.archives-ouvertes.fr/hal-03405165.

[23] M. Even and L. Massoulié. 'Concentration of Non-Isotropic Random Tensors with Applications to Learning and Empirical Risk Minimization'. In: *Proceedings of Machine Learning Reasearch*. Conference on Learning Theory, 2021. Boulder, United States: PMLR, 1st Aug. 2021. URL: https://hal.archives-ouvertes.fr/hal-03132566.

[24] L. Ganassali. 'Sharp threshold for alignment of graph databases with Gaussian weights'. In: MSML21 (Mathematical and Scientific Machine Learning). Lausanne, Switzerland, 16th Aug. 2021. URL: https://hal.archives-ouvertes.fr/hal-03139777.

[25] L. Ganassali, M. Lelarge and L. Massoulié. 'Impossibility of Partial Recovery in the Graph Alignment Problem'. In: COLT 2021 - 34th Annual Conference on Learning Theory. Boulder / Virtual, United States, 15th Aug. 2021. URL: https://hal.inria.fr/hal-03410038.

[26] G. Ghatak, S. S. Kalamkar, Y. Gupta and S. Sharma. 'A Fine-Grained Analysis of Radar Detection in Vehicular Networks'. In: IEEE GLOBECOM 2021 - IEEE Global Communications Conference. Madrid, Spain, 7th Dec. 2021. URL: https://hal.archives-ouvertes.fr/hal-03328162.

[27] V. Malik, S. Kalamkar, A. Gupta and G. Ghatak. 'Where to Deploy Reconfigurable Intelligent Surfaces in the Presence of Blockages?' In: 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). Helsinki, France: IEEE, 13th Sept. 2021, pp. 1419–1424. DOI: 10.1109/PIMRC50174.2021.9569657. URL: https://hal.inria.fr/hal-03550081.

[28] I. Shilov, H. Le Cadre and A. Bušić. 'A Generalized Nash Equilibrium analysis of the interaction between a peer-to-peer financial market and the distribution grid'. In: IEEE Smart Grid Comm 2021 - IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids. Aachen, Germany, 25th Oct. 2021. URL: https://hal.archives-ouvertes.fr/hal-03359495.

Scientific book chapters

[29] A. Devraj, A. Bušić and S. Meyn. 'Fundamental Design Principles for Reinforcement Learning Algorithms'. In: *Handbook of Reinforcement Learning and Control*. Vol. 325. Studies in Systems, Decision and Control. Springer International Publishing, 24th June 2021, pp. 75–137. DOI: 10.1007/978-3-030-60990-0_4. URL: https://hal.archives-ouvertes.fr/hal-03541756.

[30] A. Giovanidis and B. Błaszczyszyn. 'Randomised Geographic Caching and its Applications in Wireless Networks'. In: *Edge Caching for Mobile Networks*. The Institution of Engineering and Technology, 2021, pp. 371–404. URL: https://hal.archives-ouvertes.fr/hal-02994177.

Doctoral dissertations and habilitation theses

[31] H. Hendrikx. 'Accelerated Methods for Distributed Optimization'. PSL, 20th Sept. 2021. URL: https://hal.archives-ouvertes.fr/tel-03475383.

Reports & preprints

[32] F. Baccelli and S. S. Kalamkar. *On Point Processes Defined by Angular Conditions on Delaunay Neighbors in the Poisson-Voronoi Tessellation*. 12th Jan. 2021. URL: https://hal.archives-ouvertes.fr/hal-03107916.

[33] 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*. 27th Jan. 2022. URL: https://hal.archives-ouvertes.fr/hal-03546049.

[34] C. Bourdais, C. Fricker and H. Mohamed. *Mean field analysis of stochastic networks with reservation*. 21st Jan. 2022. URL: https://hal.archives-ouvertes.fr/hal-03539104.

[35] A. Coffman, A. Bušić and P. Barooah. *A unified framework for coordination of thermostatically controlled loads*. Aug. 2021. URL: https://hal.archives-ouvertes.fr/hal-03541767.

[36] C. Comte, F. Mathieu and A. Bušić. *Stochastic dynamic matching: A mixed graph-theory and linear-algebra approach*. 6th Jan. 2022. URL: https://hal.archives-ouvertes.fr/hal-03502084.

[37] S. Coste. *Sparse matrices: convergence of the characteristic polynomial seen from infinity*. 3rd June 2021. URL: https://hal.archives-ouvertes.fr/hal-03247769.

[38] S. Coste and L. Stephan. *A simpler spectral approach for clustering in directed networks*. 10th Feb. 2021. URL: https://hal.archives-ouvertes.fr/hal-03137583.

[39] B. Dubail and L. Massoulié. *Accelerating Abelian Random Walks with Hyperbolic Dynamics*. 24th June 2021. URL: https://hal.archives-ouvertes.fr/hal-03269589.

[40] C. Fricker, H. Mohamed, T. Popescu and M. Trépanier. *Stochastic Modelling of Free-Floating Car-Sharing Systems*. CIRRELT, Feb. 2021. URL: https://hal.archives-ouvertes.fr/hal-03163814.

[41] H. Hendrikx, L. Massoulié and M. Even. *Asynchrony and Acceleration in Gossip Algorithms*. 10th Feb. 2021. URL: https://hal.archives-ouvertes.fr/hal-02989459.

[42] B. M. Moreno, C. Fricker, H. Mohamed, A. Philippe and M. TREPANIER. *Mean field analysis of an incentive algorithm for a closed stochastic network*. 21st Jan. 2022. URL: https://hal.archives-ouvertes.fr/hal-03539628.

[43] P. Popineau, S. S. Kalamkar and F. Baccelli. *On Velocity-based Association Policies for Multi-tier 5G Wireless Networks*. 3rd Sept. 2021. URL: https://hal.archives-ouvertes.fr/hal-03334055.

[44] L. Stephan and L. Massoulié. *Non-backtracking spectra of weighted inhomogeneous random graphs*. 15th Feb. 2021. URL: https://hal.inria.fr/hal-03140329.