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2025 *Activity Report*

RESEARCH CENTRE: **Inria Paris Centre**

IN PARTNERSHIP WITH: **Ecole normale supérieure de Paris**

Project-Team

MATHNET

Probability and Dynamics of Geometric Networks

In collaboration with Département d'Informatique de l'Ecole Normale Supérieure

Project-Team MATHNET

Creation of the Project-Team: 2025 June 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

Keywords

Computer sciences and digital sciences

A1.2.4. – QoS, performance evaluation

A6.1.2. – Stochastic Modeling

A6.2.3. – Probabilistic methods

A8.2. – Optimization

A8.3. – Geometry, Topology

A8.6. – Information theory

A8.7. – Graph theory

A8.8. – Network science

A8.9. – Performance evaluation

Other research topics and application domains

B1.2. – Neuroscience and cognitive science

B6.2.2. – wireless networks

B6.2.3. – Satellite networks

B6.3.4. – Social Networks

B6.5. – Information systems

B7.1. – Traffic management

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1 Team members, visitors, external collaborators

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2 Overall objectives

*Math*Net, created in June 2025 as a continuation of Dyogene, focuses on two interdependent core objectives:

- Developing mathematical frameworks intended to be broadly applicable to real-world network problems.
- Exploring and validating the practical applications of these frameworks.

At the heart of the first objective lie two mathematical pillars: *stochastic geometry*, which provides probabilistic models for random spatial structures of a continuous nature (often using point processes to represent random configurations of physical entities), and *random graph theory*, which addresses abstract discrete structures such as graphs and trees.

By integrating additional mathematical theories and physical concepts—such as percolation, unimodularity, mean-field theory, and scaling laws—into the broader framework of *random geometry*, we gain new perspectives on existing models and open the door to the development of genuinely new structures. We believe these advances will be valuable for both current and future networked systems.

Mathematics plays a central role in addressing real-world network challenges. In line with this dual commitment, we tackle concrete problems across a range of application domains, with a particular emphasis on understanding the macroscopic properties of large-scale networks—insights that are not readily accessible from purely local or technical viewpoints. Ultimately, many of these challenges lie at the interface between technical feasibility and economic decision-making.

3 Research program

The research focus of *Math*Net, as established in its foundational manifesto, centers on the development of mathematical methods to address network challenges across a broad spectrum of abstraction. Our approach ranges from high-level theoretical frameworks designed for universal applicability to specialized models directly inspired by real-world engineering hurdles, always with a primary emphasis on intrinsic mathematical innovation.

These diverse methodologies are unified under the overarching paradigm of **Random Geometry**. The core components of this framework are strategically architected to tackle the distinct facets of large-scale networks:

- PERCOLATION remains a cornerstone for the study of *large-scale network connectivity*, a field pioneered by [34]. It allows for the rigorous analysis of phase transitions and global reachability within disordered systems.
- UNIMODULARITY provides the formal machinery to define and analyze *“homogeneity”* within the local structures of vast, irregular networks. This property is operationally characterized by the **Mass Transport Principle** [32], a powerful invariance tool for capturing structural relationships and balancing “flows” within a network.
- The MEAN FIELD approach, including its specialized REPLICA MEAN FIELD variants [36, 38], *bridges the gap between local interactions and global dynamics*. By approximating the influence of a node’s local environment through a collective average, it simplifies the complexity of high-dimensional interactions into tractable macroscopic behavior.

- SCALING LAWS facilitate the investigation of the *macroscopic geometric properties* of large-scale systems. Within this domain, concepts such as **Gromov-weak convergence** [33] are particularly salient for characterizing the limits of network topologies as they grow in size or density.

- HYPERUNIFORMITY, a modern concept emerging from the intersection of physics and materials science [39], offers a sophisticated lens for studying *perturbed lattice-like networks*. These systems are defined by suppressed variance in large-scale node densities. Such networks often manifest *"rigidity"*, where local configurations are fundamentally constrained by the global environment—a property we aim to leverage toward a formal **geometric network calculus**.

- Finally, SIGNAL PROCESSING [37] and SPATIAL STATISTICS [35] serve as the interface between mathematical modeling and data science, providing the requisite tools for statistical inference and learning. Complementing these, INFORMATION THEORY acts not only as the governing law of communication but also as a universal framework for statistical inference and maximum entropy modeling.

4 Application domains

We are intrested in application of our mathematical theories to specific domains, including **wireless networks**, **transportation systems**, and **life sciences**. Our work is typically conducted in collaboration with external partners, ranging from industrial organizations—such as Orange Labs, Nokia Bell Labs, Communauto, and Smovengo—to institutional partners like Assistance Publique – Hôpitaux de Paris (AP-HP), as well as academic experts in the relevant fields.

Our primary objective in these collaborations is not to develop deep technical expertise within the application domains themselves. Instead, we focus on leveraging our mathematical toolkit to tackle specific problems identified by our partners. Notable application areas include:

- **5G/6G Wireless Networks:** We study advanced architectures, specifically those utilizing Reconfigurable Intelligent Surfaces (RIS) and Non-Terrestrial Networks (NTN).

- **Transportation and Logistics:** We analyze car-sharing systems (such as the former Autolib') and bike-sharing networks to optimize fleet management and resource allocation.

- **Life Sciences and Healthcare:** We apply stochastic modeling to emergency department workflows and the study of biological neural networks.

5 Social and environmental responsibility

5.1 Footprint of research activities

The *Math*Net team is committed to minimizing the direct environmental impact of its scientific operations by adhering to principles of digital sobriety:

- **Low-Intensity Computation:** Unlike research areas dependent on heavy deep-learning training or massive data processing, our work focuses on analytical derivation and fundamental mathematics. This "pen-and-paper" approach inherently results in a minimal carbon footprint. Numerical simulations are optimized to run on standard workstations, avoiding the high energy demands of large-scale supercomputing clusters.

- **Sustainable Mobility:** We prioritize virtual collaboration and selective attendance at international conferences. For European meetings, sustainable transport options are favored to reduce the institutional carbon impact related to air travel.

5.2 Impact of research results

The primary socio-environmental contribution of our research lies in the **mathematical optimization of infrastructure**, which serves as a critical lever for sustainability:

- **Energy and Resource Efficiency:** Solving large-scale network problems through rigorous mathematics allows for precise infrastructure dimensioning. By accurately defining stability regions and scaling laws, our models prevent the over-provisioning of hardware. This leads to substantial savings in physical resources (raw materials) and operational energy consumption.
- **Green Connectivity:** Our research into Reconfigurable Intelligent Surfaces (RIS) and stochastic geometry aims to augment network capacity without a proportional increase in power density or electromagnetic exposure, promoting more efficient use of the radio spectrum.
- **Optimization of Public Services:** The application of our theoretical frameworks to urban mobility (e.g., car-sharing systems) and healthcare (e.g., emergency department workflows) contributes to the efficient management of public resources, reducing congestion and improving the quality of social services.

6 Highlights of the year

- During her delegation at Inria, Hanen Mohamed defended her HDR.

7 Latest software developments, platforms, open data

7.1 Latest software developments

7.2 New platforms

8 New results

Participants: All *MathNet*.

8.1 Developing Mathematical Frameworks

Goal: *Developing mathematical frameworks intended to be broadly applicable to real-world network problems.*

This section includes works focused on fundamental theory, including stochastic geometry, hyperuniformity, rigidity, and queuing theory. These establish the "tools" and "laws" used to understand complex systems.

1. ***On the Study of Random Measures Associated with Gaussian Processes*** [20] This thesis is devoted to the study of certain random measures and point processes arising from Gaussian fields, with a focus on their properties of almost-periodicity, rigidity, and hyperuniformity. The latter two notions form the core of this work, and we take the time to briefly define them in this introduction. Hyperuniformity is a characteristic common to a wide range of biological and physical systems, ranging from the organisation of atoms in a cell to the distribution of stars in the cosmos. It originates from the principle of least action, which states that a physical system tends to prefer a stable equilibrium when at rest. Contrary to what intuition might suggest, these stable configurations can appear locally disordered, but at the macroscopic scale, they exhibit a certain regularity, a regularity that leads to a phenomenon of hyperuniformity common to many physical systems. As for rigidity, it is a purely mathematical concept, and it involves asking whether, starting from a partially observed system of particles, it is possible to recover information about the unobserved part of the process. By information, we mean the exact number of hidden points, their centre of mass, or even their exact distribution, . . . Hyperuniformity and rigidity are not orthogonal concepts, and it has been shown that many hyperuniform processes exhibit a certain form of rigidity, at least in low dimensions. This link between hyperuniformity and rigidity is all the more surprising given that there are very few systematic methods available to study the rigidity of a particle system. In this thesis, we continue the study of these two phenomena. The first topic addressed in this work is related to the nodal lines of the Arithmetic Gaussian Random Wave. The latter are known to exhibit a variance cancellation reminiscent of hyperuniformity, as well as a phenomenon referred to as full-correlation. We show that the latter is linked with an almost-periodicity induced by the arithmetic structure of the torus. In the subsequent chapters, we move away from nodal sets and turn to the problem of generating disordered samples from random fields. To this end, we introduce a new procedure that enables the generation of stationary measures via a perturbation of their Palm measure. The study of this model is pursued in Chapter 5, where we focus on the hyperuniformity properties of these perturbed Palm processes.

2. ***Asymptotic fluctuations of smooth linear statistics of independently perturbed lattices*** *[30]* We consider the hyperuniform model of d-dimensional integer lattice perturbed by independent random variables and we investigate the large scale asymptotic fluctuations of smoothed versions of the usual counting statistics, specifically of linear statistics associated to a smooth function with rapid decay at infinity. We highlight three distinct classes of limit, depending on the dimension d and on the tails of the perturbations. On the one hand, we establish that for dimensions larger than two, central limit theorems hold under mild assumptions on the perturbations. This confirms numerical observations from physics, suggesting that even for highly correlated hyperuniform models, large dimensions favor asymptotic normality. On the other hand, in dimension one, the limiting distribution can be Gaussian, non-Gaussian with finite moments of all orders, or stable with parameter strictly between one and two. These two latter results represent rare examples of non-Gaussian limits for smooth linear statistics of hyperuniform point processes of Classes I and II.

3. ***Minimax estimation of the structure factor of spatial point processes*** *[31]* We investigate the problem of estimating the structure factor, or spectra, of stationary spatial point processes. In the first part, we establish a minimax lower bound for this estimation problem, using an approach tailored to second-order properties of spatial point processes. Although not the main focus, this methodology also extends naturally to a minimax lower bound for the estimation of the pair correlation function of spatial point processes. In the second part, we construct a multitaper estimator that achieves the optimal rate of convergence in squared risk. Under a Brillinger-mixing condition, we further establish a chi-square-type concentration bound. Finally, we propose a data-driven procedure for selecting the number of tapers, supported by an oracle inequality, and we demonstrate the practical effectiveness of the method through numerical experiments.

4. ***Decision-Epochs Matter: Unveiling Its Impact on the Stability of Scheduling With Randomly Varying Connectivity*** *[9]* A classical result in queuing theory states that in a parallel-queue single-server model, the maximum stability region is unaffected by scheduling decision epochs, and in particular is the same for preemptive and non-preemptive systems. We examine a scenario where queues are randomly connected to the server and show that, unlike the classical case, the maximum stability region strongly depends on the scheduling decision epochs. We compare three settings: decisions can be made anytime (unconstrained), decisions are made only at departures (non-preemptive), and decisions occur when a γ-rate exponential clock rings. We observe a significant reduction in the stability region in the non-preemptive setting compared to the unconstrained one, showing that a non-preemptive scheduler cannot take opportunistically advantage of the random varying connectivity. Also, in the γ-rate clock setting, one can be arbitrarily close to the maximum stability region in the unconstrained setting if we choose γ large enough. In all the settings, we show that the Longest Connected Queue (LCQ) policy achieves maximum stability. From a methodological viewpoint, we introduce a new theoretical tool called "test for fluid limits" (TFL), which offers a method to determine stability on the basis of a simple formal test.

5. ***Online matching for the multiclass stochastic block model*** *[10]* We consider the problem of sequential matching in a stochastic block model with several classes of nodes and generic compatibility constraints. When the probabilities of connections do not scale with the size of the graph, we show that under the NCOND condition, a simple max-weight type policy allows to attain an asymptotically perfect matching while no sequential algorithm attain perfect matching otherwise. The proof relies on a specific Markovian representation of the dynamics associated with Lyapunov techniques.

6. ***Functional central limit theorem for topological functionals of Gaussian critical points*** *[24]* We consider Betti numbers of the excursion of a smooth Euclidean Gaussian field restricted to a rectangular window, in the asymptotics where the window grows to $\mathbb{R}^d$. With motivations coming from Topological Data Analysis, we derive a functional Central Limit Theorem where the varying argument is the thresholding parameter, under assumptions of regularity and covariance decay for the field and its derivatives. We also show fixed-level CLTs coming from martingale based techniques inspired from the theory of geometric stabilisation, and limiting non-degenerate variance.

7. ***Higher-order Monte Carlo cluster dynamics for community detection in Euclidean graphs*** *[16]* We study GIBBS distributions with competing interactions and propose a higher-order extension of the SWENDSEN–WANG dynamics that incorporates triangular bonds. The new dynamics preserves the same stationary distribution, alleviates frustration, and yields markedly better sampling. When applied to a synthetic Euclidean-graph community-detection benchmark, our algorithm outperforms existing methods.

8. ***Poisson approximation of fixed-degree nodes in weighted random connection models*** *[23]* 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.

9. ***Hyperuniform random measures, transport and rigidity*** *[26]* This survey explores the foundational theory and recent developments in the study of hyperuniformity. We present a comprehensive mathematical framework in the context of weakly stationary random measures, emphasizing spectral characterizations and second order asymptotics. Classical examples - including determinantal point processes, Gibbs measures, and zero sets of Gaussian analytic functions - are presented in depth to illustrate core principles. We also highlight recent progress connecting hyperuniformity with optimal transport and rigidity phenomena, pointing to emerging directions in the field.

10. ***Maximal rigidity of random measure and uniqueness pairs: stealthy processes, quasicrystals and periodicity*** *[27]* This article investigates the phenomenon of maximal rigidity in spatial processes, where perfect interpolation of the process is possible from partial information, specifically, from its restriction to a strict subdomain, often resulting in a trivial tail algebra. A classical example known since the 1930's is that a time series is fully determined by its values on the negative integers if its spectrum has a gap, or at least a sufficiently deep zero. We extend such results to higher dimensions and continuous settings by establishing a connection with the concept of uniqueness pairs, rooted in the uncertainty principle of harmonic analysis. We present several other manifestations of this principle, unify and strengthen seemingly unrelated results across different models: quasicrystals and stealthy processes are shown to be maximally rigid on cones, and discrete integer-valued processes are necessarily periodic when they have a simply connected spectrum. Finally, we identify a surprising class of continuous fields with seemingly standard behavior, such as linear variance and finite dependency range, that undergo a phase transition: they are perfectly interpolable on $B(0,\rho)$ for $0 < \rho \leqslant \frac{2}{\pi}$ but exhibit no rigidity for $\rho > 2$.

11. ***Mean field analysis of stochastic networks with reservation*** *[6]* 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.

12. ***On the geometry of the stability regions of randomly modulated queuing systems*** *[18]* We study the maximum stability region (MSR) of a scheduling problem involving multiple queues, a single server, and randomly modulated dynamics. In the case where the modulation process is autonomous, takes values in a finite set, and is in stationary regime, we characterise the stability region as a Minkowski sum of deGua simplices, structures known as *cephoids* in the convex geometry literature. Beyond endowing the stability region with a rich mathematical structure, this apparently novel connection enables an explicit description of the MSR in the 2-queue case, and provides a simple iterative scheme to obtain its minimal H-description in the general case.

13. ***Rigidity of random stationary measures and applications to point processes*** *[28]* The number rigidity of a point process P entails that for a bounded set A the knowledge of P on A^c a.s. determines $P(A)$; the k-order rigidity means we can recover the moments of $P1_A$ up to order k. We show that there is k-rigidity if the continuous component s of P's structure factor has a zero of order k in 0, by exploiting a connection with Schwartz' Paley-Wiener theorem for analytic functions of exponential type; these results apply to any random L^2 wide sense stationary measure on $\mathbb{R}^d$ or $\mathbb{Z}^d$. In the continuous setting, these local conditions are also necessary if s has finitely many zeros, or is isotropic, or at the opposite separable. This explains why no model seems to exhibit rigidity in dimension $d \geq 3$, and allows to efficiently recover many recent rigidity results about point processes. In the discrete setting, these results hold provided $\#A > 2k$. We derive new results about models of cluster lattices and give the first example of a stationary point process $P \subset \mathbb{R}^d$ exhibiting arbitrary low decay of the structure factor in 0, hence arbitrary high order of rigidity. For a continuous Determinantal point process with kernel κ, k-rigidity is equivalent to $(1 - \widehat{\kappa^2})^{-1}$ having a zero of order $2k$ in 0, which answers questions on completeness and number rigidity. We also explore the consequences of these statements in the less tractable realm of Riesz gases.

14. ***Stochastic domination and lifts of random variables in percolation theory*** *[29]* Consider some matrix waiting for its coefficients to be written. For each column, sample independently one Bernoulli random variable of some parameter p. Seeing all this and possibly using extra randomness, Alice then chooses one spot in each column, in any way she wants. When the Bernoulli random variable of some column is equal to 1, the number 1 is written in the chosen spot. When the Bernoulli random variable of a column is 0, nothing is done on this column. We prove that, using extra randomness, it is possible for Bob to fill the empty spots with well chosen 0's and 1's so that the entries of the matrix are independent Bernoulli random variables of parameter p. We investigate various generalisations and variations of this problem, and use this result to revisit and generalise (nonstrict) monotonicity of the percolation threshold p_c with respect to some sort of graph-quotienting, namely fibrations. In a second part, which is independent of the first one, we revisit strict monotonicity of p_c with respect to fibrations, a result that naturally requires more assumptions than its nonstrict counterpart. We reprove the bond-percolation case of the result of Martineau and Severo without resorting to essential enhancements, using couplings instead.

15. ***On a class of dynamical Poisson-Voronoi tessellations*** *[21]* Consider a dynamical network model featuring mobile stations on the Euclidean plane. The initial locations of the stations are given by a homogeneous Poisson point process. The stations are all moving at a constant speed and in a random direction. Consider fixed users located in the Euclidean plane, which are served by the mobile stations. Each user stays connected to the nearest station at any given point of time. Since the stations are moving, an user disconnects and connects with different stations over time, by always selecting which ever station is the closest. This gives rise to a dynamical version of the Poisson-Voronoi tessellation. The focus of this paper is on the sequence of "handover" events of a typical user, which are the epochs when its association changes. This defines a point process on the time-axis, the "handover point process". We show that this point process is stationary and we determine its main properties, in particular its intensity and the joint distribution of its inter-event times. We also analyze the handover Palm distributions of several variables of practical interest. This includes the distance to the closest mobile stations and the point process of all other mobile stations at handover epochs. The analysis is conducted both in the single-speed and in the multi-speed scenarios. It leads to the identification of the three dimensional state variables that "Markovize" the association dynamics. The analysis is based on a specific system of non-compact particles. The motivations are in the modeling of low or medium orbit satellite wireless communication networks. The model studied here is a planar "caricature" of this problem, which is initially defined on the sphere.

8.2 Exploring and Validating Practical Applications

Goal: *Exploring and validating the practical applications of the aforementioned frameworks.*

This section covers applications of the aforementioned theories to specific domains, including 5G/6G wireless networks—specifically those utilizing reconfigurable intelligent surfaces (RIS) and non-terrestrial networks (NTN)—as well as car-sharing systems (Autolib'), emergency department workflows, and biological neural networks.

16. ***On multiclass spatial birth-and-death processes with wireless-type interactions*** *[8]* This paper studies a multiclass spatial birth-and-death (SBD) processes ona compact region of the Euclidean plane modeling wireless interactions. In thismodel, users arrive at a constant rate and leave at a rate function of the inter-ference created by other users in the network. The novelty of this work lies inthe addition of service differentiation, inspired by bandwidth partitioning presentin 5G networks: users are allocated a fixed number of frequency bands and onlyinterfere with transmissions on these bands.The first result of the paper is the determination of the critical user arrival ratebelow which the system is stochastically stable, and above which it is unstable.The analysis requires symmetry assumptions which are defined in the paper. Theproof for this result uses stochastic monotonicity and fluid limit models. Themonotonicity allows one to bound the dynamics from above and below by twoadequate discrete-state Markov jump processes, for which we obtain stability andinstability results using fluid limits. This leads to a closed form expression for thecritical arrival rate. The second contribution consists in two heuristics to estimatethe steady-state densities of all classes of users in the network: the first one relieson a Poisson approximation of the steady-state processes. The second one uses acavity approximation leveraging second-order moment measures, which leads tomore accurate estimates of the steady-state user densities. The Poisson heuristicalso gives a good estimate for the critical arrival rate.

17. ***Performance Guarantees of Cellular Networks with Hardcore Regulation and Scheduling*** *[14]* Providing performance guarantees is one of the critical objectives of recent and future communication networks, toward which regulations, i.e., constraints on key system parameters, have played an indispensable role. This is the case for large wireless communication networks, where spatial regulations (e.g., constraints on intercell distance) have recently been shown, through a spatial network calculus, to be essential for establishing provable wireless link-level guarantees. In this work, we focus on performance guarantees for the downlink of cellular networks where we impose a hardcore (spatial) regulation on base station (BS) locations and evaluate how BS scheduling (which controls which BSs can transmit at a given time) impacts performance. Hardcore regulation is the simplest form of spatial regulation that enforces a minimal distance between any pair of transmitters in the network. Within this framework of spatial network calculus, we first provide an upper bound on the power of total interference for a spatially regulated cellular network, and then, identify the regimes where scheduling BSs yields better link-level rate guarantees compared to scenarios where base stations are always active. The hexagonal cellular network is analyzed as a special case. The results offer insights into what spatial regulations are needed, when to choose scheduling, and how to potentially reduce the network power consumption to provide a certain target performance guarantee.

18. ***Statistical Learning of Traffic Load from Demand in Wireless Cellular Networks: A Cell-by-Cell Approach*** *[13]* A statistical approach is proposed to predict the specific load of each cell in operational wireless networks, using traffic demand as the main variable. Unlike a global linear model, which is fitted using data from all cells uniformly without considering the specific characteristics of each cell, the cellwise linear approach is distinguished by two key elements: (i) a unidimensional model, in which the load of each cell is predicted solely based on its own traffic demand, and (ii) a multidimensional model, in which the traffic demand of all the cells is incorporated. Using large-scale real-world data, it is shown that the unidimensional model outperforms global approaches in terms of accuracy. While additional flexibility and improvements are offered by the multidimensional model in specific scenarios, particularly under high traffic conditions, its coefficients often seem to lack physical interpretability, even when using ridge regularization. This underscores the need for more advanced regularization techniques to be developed and particularly, ones that account for the geometry of wireless networks.

19. ***Localized Statistical Learning of Cell Loads in Cellular Networks*** *[12]* Accurate cell load prediction is crucial for efficient wireless networks. This paper investigates localized statistical learning, using a varying number of input neighboring cells k to optimize load estimation. Using real-world operational data, different prediction methods are benchmarked, such as neural networks (NNs), linear fitting and ridge regularization. Experiments compellingly show that NNs incorporating activation functions achieve superior prediction performance. An optimal range for k is identified to be around 20-30 neighbors, demonstrating an essential balance between model complexity and generalization. Notably, the study affirms the robustness of this approach against stochastic training variations and highlights the benefits of sufficient training data. Thus, this work underscores the efficacy of localized, non-linear models, offering robust insights and paving the way for deep learning approaches to cell load prediction.

20. ***Statistical Learning for Quality of Service Evaluation and Dimensioning of Wireless Networks*** *[19]* Accurate prediction of the cellular network load relative to a traffic demand is essential for strategic network planning and resource management. This thesis evaluates a range of predictive models, from physics-based mathematical frameworks to data-driven statistical learning methods, to identify the most robust and efficient approaches for this task.For short-term forecasting, the investigation reveals that cell specific, complex non-linear models achieve the highest accuracy. Specifically, a neural network that considers traffic from a localized neighborhood of nearby cells outperforms global benchmarks. This demonstrates the importance of capturing local spatial dependencies, while carefully managing model complexity to avoid the overfitting, that occurs when using data from the entire network.Another major contribution of this work is the analysis of long-term performance in the presence of temporal drift, namely the natural evolution of network dynamics over time. On horizons extending up to two years, a striking reversal in performance is observed. The complex models, so effective in the short term, suffer significant accuracy degradation. In their place, physics-based and simpler models demonstrate remarkable resilience. Indeed, a basic data-driven model that uses only a cell's own historical traffic consistently delivers the most reliable long-term forecasts, rivaled only by the aforementioned mathematical model.This thesis concludes that a fundamental trade-off exists between short-term accuracy and long-term stability. For the strategic, long-horizon applications required by network operators, model simplicity and resistance to overfitting thus prove to be more critical factors for success than the capacity to model intricate, transient spatial patterns.

21. ***Data Science: From Statistics to Machine Learning and Deep Learning, with Applications to Wireless Networks*** *[25]* This book offers a rigorous, self-contained introduction to the mathematical foundations of machine learning, from its roots in multivariate statistics to modern deep learning architectures. A defining feature of this work is its commitment to mathematical rigor; unlike approaches that treat algorithms as "black boxes," key concepts are introduced through precise definitions and established via theorems with complete proofs. This principled approach is particularly evident in the formal treatment of measurability issues, a topic often glossed over in the learning theory literature.The book is organized into three parts. The first two parts cover the theoretical core of multivariate statistics and machine learning, including linear models, logistic regression, learnability (VC theory), and neural networks.The third part bridges the gap between theory and practice with an in-depth case study on predicting Quality of Service (QoS) in large-scale wireless networks. Using operational data from a major European operator, we demonstrate how the theoretical frameworks are implemented and validated in a real-world engineering context. By combining a rigorous theoretical exposition with a significant practical application, this book aims to provide a complete and actionable guide for both researchers and practitioners in data science.

22. ***Large-scale analysis of load-balancing policies for free-floating car-sharing models*** *[15]* In free-floating (FF) car-sharing systems, FF cars share parking spaces in public space with much more numerous private cars. The system is modeled as a closed queueing network with two classes of customers, FF and private cars, with different orders of magnitude. They move between N nodes, each with a large capacity CN , C positive. Mean-field techniques are adapted to the presence of private cars, which act as a fast-varying random environment. This allows us to study the impact of load-balancing policies on the distribution of the number of FF cars per zone when the system gets large. For two load-balancing policies, respectively modifying the routing probabilities and the pick-up rates, we obtain an explicit distribution, a binomial negative distribution driven by a fixed point equation. The influence of parameters on performance is derived.

23. ***Thermodynamical limits for models of car-sharing systems: the Autolib' example*** *[5]* We analyze mean-field equations obtained for models motivated by a large station-based car-sharing system in France called Autolib'. The main focus is on a version where users reserve a parking space when they take a car. In a first model, the reservation of parking spaces is effective for all users and capacity constraints are ignored. The model is carried out in the thermodynamical limit, that is when the number N of stations and the number of cars M_N tend to infinity, with $U = \lim_{N\to\infty} M_N/N$. This limit is described by Kolmogorov's equations of a two-dimensional time-inhomogeneous Markov process depicting the numbers of reservations and cars at a station. It satisfies a non-linear differential system. We prove analytically that this system has a unique solution, which converges, as $t \to \infty$, to an equilibrium point exponentially fast. Moreover, this equilibrium point corresponds to the stationary distribution of a two-queue tandem (reservations, cars), which is here always ergodic. The intensity factor of each queue has an explicit form obtained from an intrinsic mass conservation relationship. Two related models with capacity constraints are briefly presented: the simplest one with no reservation leads to a one-dimensional problem; the second one corresponds to our first model with finite total capacity K.

24. ***Stability and renormalization of Jackson networks with non-idling mobile servers*** *[22]* A tandem of two queues sharing a pool of servers, where users take the time to switch to thesecond queue, is used to model a typical pathway through an emergency department (ED), wherepatients undergo two consultations separated by diagnostic tests. In this article, explicit conditionsfor ergodicity and transience are given and proven via Foster's criterion, using a linear Lyapunovfunction. This result is extended to a Jackson network, with the key difference that the nodes sharea pool of servers, with a non-idling service policy. Further, the delay times for customers to movefrom one node to another must be taken into account. This covers some of the main features ofmodels for emergency departments, namely priorities (triage) between patients. In the case of thetandem queue, by scaling the arrival rate and the number of servers by N, we obtain a renormalizedprocess converging to the solution of an ordinary differential equation (ODE) subject to boundaryconditions. When the system is ergodic, we discuss the solution of this ODE as $t \to \infty$.

25. ***Analysis of a Spatially Correlated Vehicular Network Assisted by Cox-Distributed Vehicle Relays*** *[4]* In vehicle-to-everything (V2X) communications, roadside units (RSUs) play an essential role in connecting various network devices. In some cases, users may not be well-served by RSUs due to congestion, attenuation, or interference. In these cases, vehicular relays associated with RSUs can be used to serve those users. This paper uses stochastic geometry to model and analyze a spatially correlated heterogeneous vehicular network where both RSUs and vehicular relays serve network users such as pedestrians or other vehicles. We present an analytical model where the spatial correlation between roads, RSUs, relays, and users is systematically modeled via Cox point processes. Assuming users are associated with either RSUs or relays, we derive the association probability and the coverage probability of the typical user. Then, we derive the user throughput by considering interactions of links unique to the proposed network. This paper gives practical insights into designing spatially correlated vehicular networks assisted by vehicle relays. For instance, we express network performance such as user association, signal-to-interference (SIR) coverage probability, and network throughput as the functions of network key geometric parameters. In practice, this helps one to optimize the network so as to achieve ultra reliability or maximum user throughput of the vehicular networks by varying key aspects such as the relay density or the bandwidth for relays.

26. ***A Stochastic Geometry Framework for Performance Analysis of RIS-assisted OFDM Cellular Networks*** *[11]* The reconfigurable intelligent surface (RIS) technology allows one to engineer spatial diversity in complex cellular networks. This paper provides a stochastic geometry framework for the system-level performance assessment of RIS-assisted networks. To account for the inherent randomness in the spatial deployments of base stations (BSs) and RISs, we model the RIS placements as point processes (PPs) conditioned on the associated BSs, which are modeled by a Poisson point process (PPP). We assume that the system uses the orthogonal frequency division multiplexing (OFDM) technique to exploit the multipath diversity provided by RISs. The downlink coverage probability and ergodic rate can be evaluated when RISs operate as batched powerless beamformers. The resulting analytical expressions provide a general methodology for assessing the impact of a parameterized RIS model on system performance. These RIS PPs can be adapted based on the deployment strategy. We focus on modeling the RISs as a Matérn cluster process (MCP), where each RIS cluster is a finite PPP within a ring centered on its associated BS. This model connects link-level knowledge to system-level impacts, such as overall interference and the effects of imperfect channel state information (CSI). It also evaluates key RIS deployment parameters, including batch size and RIS density. Furthermore, we analyze a variant of RIS placement in which RISs are deployed around coverage holes to demonstrate the framework's flexibility and applicability. Numerical evaluations of the analytical expressions and Monte-Carlo simulations jointly validate the proposed analytical approach and provide valuable insights into the design of future RIS-assisted cellular networks.

27. ***How Much Can Reconfigurable Intelligent Surfaces Augment Sky Visibility: A Stochastic Geometry Approach*** *[7]* This paper uses the theory of point processes and stochastic geometry to quantify the sky visibility experienced by users located in an outdoor environment. The general idea is to represent the buildings of this environment as a stationary marked point process, where the points represent the building locations and the marks their heights. The point process framework is first used to characterize the distribution of the blockage angle, which limits the visibility of a typical user into the sky dueto the obstruction by buildings. In the context of communications,this distribution is useful when users try to connect to the nodes of an aerial or non-terrestrial network in a Line-of-Sight way. Within this context, the point process framework can also be used to investigate the gain of connectivity obtained thanks to Reconfigurable Intelligent Surfaces. Assuming that such surfaces are installed on the top of buildings to extend the user's sky visibility, this point process approach allows one to quantify the gain in visibility and hence the gain in connectivity obtained by the typical user. The distributional properties of visibility-relatedmetrics are cross-validated by comparison to simulation results and 3GPP measurements

28. ***A Novel Analytical Model for LEO and MEO Satellite Networks based on Cox Point Processes*** *[2]* This work develops an analytical framework for downlink low Earth orbit (LEO) or medium Earth orbit (MEO) satellite communications, leveraging tools from stochastic geometry. We propose a tractable approach to the analysis of such satellite communication systems, accounting for the fact that satellites are located on circular orbits. We accurately incorporate this geometric property of LEO or MEO satellite constellations by developing a Cox point process model that jointly produces orbits and satellites on these orbits. Our work contrasts with previous modeling studies that presumed satellite locations to be entirely random, thereby overlooking the fundamental fact that satellites are jointly positioned on orbits. Employing this Cox model, we analyze the network performance experienced by users located on Earth. Specifically, we evaluate the no-satellite probability of the proposed network and the Laplace transform of the interference created by such a network. Using it, we compute its SIR (signalto-interference) distribution, namely its coverage probability. By presenting fundamental network performance as functions of key parameters, this model allows one to assess the statistical properties of downlink LEO or MEO satellite communications and can thus be used as a system-level design tool to operate and optimize forthcoming complex LEO or MEO satellite networks.

29. ***Stochastic Geometry and Dynamical System Analysis of Walker Satellite Constellations*** *[3]* In practice, low Earth orbit (LEO) and medium Earth orbit (MEO) satellite networks consist of multiple orbits which are populated with many satellites. A widely used spatial architecture for LEO or MEO satellites is the Walker constellation, where the longitudes of orbits are evenly spaced and the satellites are equally spaced along the orbits. In this paper, we develop a stochastic geometry model for the Walker constellations. This proposed model enables an analysis based on dynamical system theory, which allows one to address essential structural properties such as periodicity and ergodicity. It also enables a stochastic geometry analysis under which we derive the performance of downlink communications of a typical user at a given latitude, as a function of the key constellation parameters.

30. ***Spectrum Coexistence Between Passive Satellites and Terrestrial Network via Chernoff Bounds*** *[17]* We develop tractable characterizations of the interference resulting from terrestrial cellular networks radiating towards passive satellite sensing receivers. Such a setting has important implications for the future allocation and terrestrial use of spectrum in the 100 to 300 GHz band. Building on a recently developed stochastic geometry approach, we focus on the outage probability experienced by to a constellation of satellite sensors, which depends upon the distribution of the interference experienced by a typical satellite sensor. The distribution is a function of spatial and temporal randomness. We obtain upper bounds on the outage probability using a large deviation technique for Poisson shot noise, which is a novel adaptation of the Chernoff technique. This analytical method allows for the distribution of the interference to be tightly and tractably bounded. Our analysis theoretically confirms that the satellite sensor's outage probability decreases exponentially as the interference constraint is relaxed, and allows bounding of very low outage probability values, which would be very difficult to simulate.sarotte:hal-05523562

31. ***Subthreshold variability of neuronal populations driven by synchronous synaptic inputs*** *[1]* Abstract Even when driven by the same stimulus, neuronal responses are well-known to exhibit a striking level of spiking variability. In-vivo electrophysiological recordings also reveal a surprisingly large degree of variability at the subthreshold level. In prior work, we considered biophysically relevant neuronal models to account for the observed magnitude of membrane voltage fluctuations. We found that accounting for these fluctuations requires weak but nonzero synchrony in the spiking activity, in amount that are consistent with experimentally measured spiking correlations. Here we investigate whether such synchrony can explain additional statistical features of the measured neural activity, including neuronal voltage covariability and voltage skewness. Addressing this question involves conducting a generalized moment analysis of conductance-based neurons in response to input drives modeled as correlated jump processes. Technically, we perform such an analysis using fixed-point techniques from queuing theory that are applicable in the stationary regime of activity. We found that weak but nonzero synchrony can consistently explain the experimentally reported voltage covariance and skewness. This confirms the role of synchrony as a primary driver of cortical variability and supports that physiological neural activity emerges as a population-level phenomenon, especially in the spontaneous regime. Author summary Owing to the sheer complexity of biological networks, identifying the design principles for neural computations will only be possible via the simplifying lens of theory. However, to be accepted as valid explanations, theories need to be implemented in idealized neuronal models that can reproduce key aspects of the measured neural activity. Only then can these theories be subjected to experimental validation. In this manuscript, we address this requirement by asking: under which conditions can biophysically relevant neuronal models reproduce physiologically realistic subthreshold activity? We answer this question by focusing on the membrane voltage correlation and skewness, two key statistical signatures of the variable neuronal responses that have been well characterized in behaving mammals. As our core result, we show that the presence of weak but nonzero spiking synchrony is necessary to elicit physiological neuronal responses. The identification of synchrony as a primary driver of neural activity runs counter to the currently prevailing asynchronous state hypothesis, which serves as the basis for many leading neural network theories. Recognizing a central role for synchrony supports that neural computations fundamentally emerge at the collective level rather than as the result of independent parallel processing in neural circuits.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Bartłomiej Błaszczyszyn , Lucas Darlavoix .

9.1.1 CIFRE with Orange.

Contract with Orange (2023–2025) for the co-advising a PhD student of Orange, Lucas Darlavoix, titled “Machine Learning for QoS evaluation and dimensioning of wireless cellular networks”. PhD defended in 2025 [13].

9.1.2 Collaboration research with Smovengo

Participants: Christine Fricker, Raphaël Lachièze-Rey, Samuel Molano-Quintana, Armand De Cacqueray.

An exploratory acction *Flow Estimation and Self-Service Vehicle Regulation* between Inria and Smovengo Paris was validated in 2024. One-year contract with this operator of a bike-sharing service was signed in 2025. Interns Samuel Molano-Quintanaand Armand De Cacueraywere hired by Inriaa within this project.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Alliance Communauto Montreal

Participants: Christine Fricker.

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

10.1.2 STAR South Korea-France

Participants: François Baccelli, Nahuel Soprano Loto, Philippe Sarotte.

Hubert Curien STAR South Korea-France three-year project (2024-2027), led by François Baccelli on the Inria side and Chang Sik Choi [Hongik University] on the South Korean side, focuses on modeling Non-Terrestrial Networks (NTN) in low Earth orbit using stochastic geometry.

10.2 European initiatives

10.2.1 SNS INSTINC

Participants: François Baccelli, Emanuele Mengoli, Nahuel Soprano Loto.

A project titled *"Joint Sensing and Communications for Future Communications for Future Interactive, Immersive, and Intelligent Connectivity Beyond Communications* INSTINCT within the Smart Networks and Services (SNS) Joint Undertaking, a collaboration between the EU Council and industrial partners aimed at advancing Europe's leadership in 6G technology and accelerating 5G deployment. Inria received funding for its individual program, coordinated by Jean-Marie Gorce at INSA-Lyon, with participation from François Baccelli, Nahuel Soprano Loto, and a PhD student, Emanuele Mengoli.

10.3 National initiatives

10.3.1 PEPR "5G et Réseaux du Futur"

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Emanuele Mengoli, Philippe Sarotte, Nahuel Soprano Loto.

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*.

10.3.2 PGMO

Project "Charging issues in vehicle-sharing systems: Stochastic modeling and large scale analysis" within the Gaspard Monge Program for optimization, operations research and their interactions with data sciences funded by the Fondation Mathématique Jacques Hadamard (FMJH) led by Christine Fricker.

Participants: Christine Fricker, Alessia Rigonat, Hanen Mohamed.

10.3.3 RT MAIAGES

Participants: All *Math*Net.

Members of *Math*Net participate Thematic Network MAIAGES, which focuses on Mathematics for Imaging, Learning, and Stochastic Geometry. This integration broadens the scope and fosters new collaboration opportunities. As a continuation of GeoSto (GdR 3477) on Stochastic Geometry.

10.4 Regional initiatives

10.4.1 Smart Waves — PSL Research Program

Participants: Bartłomiej Błaszczyszyn, , Simon Steinlin.

Part of the PSL University Strategic Research Programs, "Smart Waves" (coordinated by Julien de Rosny, ESPCI Paris) is a multidisciplinary initiative focused on controlling and shaping waves across various domains, including optics, acoustics, microwaves, and seismology. The program addresses major societal challenges in healthcare, communications, and sustainable development.

*Math*Net, in collaboration with DIENS, has been actively involved in structuring this program. A key contribution is the supervision of the PhD project GeoSto4RIS (Stochastic Geometry for Reconfigurable Intelligent Surfaces) of Simon Steinlin, which applies stochastic geometry to the modeling and optimization of next-generation smart surfaces.

10.4.2 IA4IDF

Participants: Christine Fricker, Alessia Rigonat.

Contract of three years, started at 2024, with Île-de-France region via the DIM (Domain of Major Interest) program IA4IDF (Artificial Intelligence for Île-de-France) for adwising PhD thesis of Alessia Rigonaton ”Modeling and AI prediction fo car-sharing”.

10.4.3 LINCS

Participants: François Baccelli, Bartłomiej Błaszczyszyn, Anne Bouillard, Ashutosh Balakrishnan, Sanjoy Kumar Jhawar, Emanuele Mengoli, Lucas Darlavoix.

The team is also affiliated with the LINCS, a research center co-founded by Inria, Institut Mines-Télécom, UPMC, and Alcatel-Lucent Bell Labs (now Nokia Bell Labs). LINCS focuses on research and innovation in future information and communication networks, systems, and services. Many of our members and students actively participate in selective LINCS activities. Students working under CIFRE agreements (Industrial Agreements for Training through Research) (e.g, with *Orange Labs*) typically spend part of their time at the premises of their industrial employers, fostering strong industry-academia collaborations.

10.5 Public policy support

10.5.1 Inria-AP-HP Challenge Urge

Participants: Christine Fricker.

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

11 Dissemination

Participants: All *Math*Net.

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

- **Seminar** *Math*Net organizes a weekly scientific seminar coordinated by a committee including Paul-Pierre RaxNahuel Soprano Loto, and Sanjoy Kumar Jhawar. Among our speakers in 2025 are: Matteo D'Achille (Université Paris-Saclay, LMO), Isabella Ziccardi (Université Paris Cité, IRIF), Shuangping Li (Stanford University), Louis Hauseux (INRIA, NEO), Nicolas Chenavier (Université du Littoral Côte d'Opale), Céline Comte (LAAS, Toulouse), Emma Horton (University of Melbourne), Benedikt Jahnel (WIAS Berlin; TU Braunschweig), Andrés Ferragut (Universidad ORT Uruguay), Matthieu Jonckheere (LAAS, Toulouse), Inés Armendáriz (Universidad de Buenos Aires, Conicet – IME – Universidade de São Paulo), Roman Gambelin (Universität Duisburg-Essen), Mathis Rost (Chalmers University), Thomas Hira (IRIT, Toulouse).

- Alessia Rigonat is in charge of organizing the *Math*Net reading group. In 2025, speakers included Gabriel Mastrilli, Philippe Sarotte, and Nahuel Soprano Loto, among others.

- François Baccelli organized the Workshop on "System Level Analysis of Non-Terrestrial Networks" June 3, 2025, at The 2025 EuCNC & 6G (European Conference on Networks and Communications) & 6G Summit, Poland.

- Bartłomiej Błaszczyszyn organized the contributed session on "Advances in Statistical Inference for Spatial Point Processes" at SPA 2025 – 44th Conference on Stochastic Processes and their Applications, Wrocław, Poland, July 14–18, 2025.

- François Baccelli organized a session "Way To 6G Workshop" at 33rd International Symposium on the Modeling, Analysis, and Simulation of Computer and Telecommunication System (MASCOT25) October 21-23, 2025 at Sorbonne University in Paris.

- **Conference on Random Geometry, Graphs, and Extremes** *Math*Net co-organized the third edition of this conference in Dubrovnik (Croatia), October 27–31, 2025. In addition to providing financial support, Bartłomiej Błaszczyszynparticipated in the scientific board. While the event has historically focused on extreme value theory, this year's themes were expanded to include point processes, stochastic geometry, random graphs, and related topics.

Member of the conference program committees

- Christine FrickerTCP member of IFIP WG 7.3 Performance 2025 conference, 11-15/11/2025, Amsterdam, Netherlands.

Reviewer - reviewing activities

- Raphaël Lachièze-Rey: reviewer for PTRF, AIHP, CIMP, AoAP, SPA, EJP.

11.1.2 Talks and posters

François Baccelli

- OPECST (Office Parlementaire d'Évaluation des Choix Scientifiques et Technologiques), Online on La Chaîne Parlementaire, January 23, 2025; invited presentation in connection with the 2024 AS report on "Grandes constellations de satellites : enjeux et impacts".
- Géométries aléatoires et applications, Collège de France, Paris, January 28–29, 2025; invited lecture on "Sur les Graphes Aléatoires Unimodulaires."
- IEEE WiOpt SPASWIN Workshop, Linköping, Sweden, May 26, 2025; Keynote Lecture on "Stochastic Geometry and Dynamical System Analysis of Non-Terrestrial Networks."
- The 2025 EuCNC & 6G (European Conference on Networks and Communications) & 6G Summit, Poland, June 3–5, 2025; talk on "How Much Can Reconfigurable Intelligent Surfaces Augment NTN Connectivity: A Stochastic Geometry Approach".
- LINCS Annual Workshop, Palaiseau, France, July 10–11, 2025; talk on "Stochastic Geometry and Dynamical System Analysis of Walker Satellite Constellations".
- Invited lecture at the Seminar "Interacting Random Systems" Weierstrass Institute (WIAS), Berlin, Germany, November 14, 2025; on "On a Class of Dynamical Poisson-Voronoi Tessellations."
- IEEE Globecom 2025, Taipei, Taiwan, December 20, 2025; talk on "Performance Guarantees of Cellular Networks with Hardcore Regulation and Scheduling"

Bartłomiej Błaszczyszyn

- SPA 2025 – 44th Conference on Stochastic Processes and their Applications, Wrocław, Poland, July 14–18, 2025; talk on "Estimating the hyperuniformity exponent of point processes"
- LINCS Seminar, Palaiseau, France, October 8, 2025; invited talk on "Estimating the hyperuniformity exponent of point processes".

Christine Fricker

- Invited talk at "Un quart de siècle pour un quart de plan", Marseille, France, April 15–17, 2025; entitled "Product-form for the analysis of large Jackson networks: application to bike/car sharing systems."

Sanjoy Kumar Jhawar

- LINCS Reading Group on Network Theory, Paris, January 2025; talk on "Sharp phase transitions in discrete and continuum percolation."
- The 2025 EuCNC & 6G (European Conference on Networks and Communications) & 6G Summit, Poland, June 3–5, 2025; talk on "Handover frequency in dynamic terrestrial communication networks."
- LINCS Annual Workshop, Palaiseau, France, July 10–11, 2025; talk on "Handover frequency in dynamic terrestrial communication networks."
- Invited seminar, LIP6-NPA Group, Sorbonne Université, Paris, October 2025; talk on "Handover frequency in dynamic terrestrial communication networks."
- Invited seminar, ETIS-ICI Group, Paris, October 2025; talk on "Handover frequency in dynamic terrestrial communication networks."
- 33rd International Symposium on the Modeling, Analysis, and Simulation of Computer and Telecommunication System (MASCOT25) October 21-23, 2025 at Sorbonne University in Paris; talk on "Handover frequency in dynamic terrestrial communication networks."

Raphaël Lachièze-Rey

- The 20th Anniversary of the Fourth Moment Theorem, University of Luxembourg, Belval Campus, December 11–12, 2025.
- Random Geometry, Graphs and Extremes, Dubrovnik, Croatia, October 27–31, 2025; talk on "Rigidity od random measures"
- TDA Danish Summer School, Aarhus, Denmark, August 4–8, 2025; mini-course on "Gaussian excursions and Topological Data Analysis."
- GeoSto Days, Grenoble, France, June 23–27, 2025; mini-course on "Hyperuniformity."

Gabriel Mastrilli

- Random Geometry, Graphs and Extremes, Dubrovnik, Croatia, October 27–31, 2025; talk on "Asymptotic fluctuations of smooth linear statistic of independently perturbed lattices."
- SPA 2025 – 44th Conference on Stochastic Processes and their Applications, Wrocław, Poland, July 14–18, 2025; talk on "Minimax Estimation of the Structure Factor of Spatial Point Processes."
- GéoSto 2025 – Géométrie Stochastique, Grenoble, France, June 23–27, 2025; talk on "Estimating the Hyperuniformity Exponent of Spatial Point Processes."
- 16th Workshop on Spatial Statistics and Image Analysis in Biology, Smögen, Sweden, June 2–5, 2025; talk on "Minimax Estimation of the Structure Factor of Spatial Point Processes."
- JEDS 2025 – Journée des Étudiants en Doctorat de Statistique, Rennes, France, May 16, 2025; talk on "Estimating the Spectral Properties of Spatial Point Processes."
- *Math*Net Reading Group, INRIA Paris, France, March 2025; lecture series on "Introduction to Minimax Theory for Spatial Point Processes: First- and Second-Order Estimation" (2 lectures).
- Probability and Statistics Seminar, University of Poitiers, France, February 2025; invited talk on "Estimating the Hyperuniformity Exponent of Spatial Point Processes."

Emanuele Mengoli

- The 2025 EuCNC & 6G (European Conference on Networks and Communications) & 6G Summit, Poland, June 3–5, 2025; Demo Booth "INSTICT" presentation on the latest developments in 6G and Smart Networks.

Alessia Rigonat

- Product-Form Probability Distributions Workshop, Eindhoven, Netherlands, May 20–23, 2025; poster on "Mean-field analysis of a multi-scale Jackson network with two classes of customers: guessing the limiting invariant distribution."
- *Math*Net Seminar, Inria, June 23, 2025; talk on "Large-scale analysis of a multi-scale Jackson network with two classes of customers."
- INFORMS Applied Probability Society Conference, Atlanta, USA, June 30–July 3,; talk on "Large-scale analysis of multi-scale Jackson-type networks with two types of customers."
- IFIP WG 7.3 Performance 2025 Conference, Amsterdam, Netherlands, November 25–27, 2025; talk on "Large-scale analysis of load-balancing policies for free-floating car-sharing models."

Philippe Sarotte

- ICC 2025 – IEEE International Conference on Communications, Montreal, Canada, June 8–12, 2025; talk on "Satellite Communication."
- Dolomites Workshop 2026 – Mean-field systems in finance, neurosciences and AI, Alba di Canazei, Italy, January 2026; talk on "Interference Queuing Network."
- AEP 13 – 13ème Atelier en Évaluation des Performances, IRIT, Toulouse, France, December 2–4, 2024; attendance only.

- PhD Seminar – MathNet Team, INRIA Paris, France, 2025; talk on ongoing doctoral research results.
- Summer School: PDE and Probability, Sorbonne Université, Paris, France, June 16–27, 2025; attendance only

Nahuel Soprano Loto

- IFIP WG 7.3 Performance 2025 Conference, Amsterdam, Netherlands; talk on "On the geometry of the stability regions of randomly modulated queuing systems."
- INSTINCT Plenary Meeting, Berlin, November 25–27, 2025; talk on "Sequential sensing in a Poisson field of sensors."
- 5-part lecture series in the *MathNet* Reading Group, June–July 2025; on "The geometry of the stability regions of randomly modulated queuing systems."

11.1.3 Leadership within the scientific community

- Raphaël Lachièze-Reyis a member of the Fondation Sciences Mathématiques de Paris (FSMP) steering committee and the FSMP postdoc jury.
- Raphaël Lachièze-Reyis a member of the Scientific Council of the Laboratory MAP5.

11.1.4 Scientific expertise

- Raphaël Lachièze-Reyserved as a reviewer for GACR (Czech science foundation).

11.1.5 Research administration

François Baccelli is one of the four co-funding members of the new "Centre National Réseaux et Systèmes pour la Transformation Numérique" funded by IMT in 2024.

11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

Exercise classes/TD, Introduction to probability, Sorbonne University (36h plus correction of copies)

11.2.1 Supervision

PhD defended

- Lucas Darlavoix, "Statistical Learning for Quality of Service Evaluation andDimensioning of Wireless Networks " [19], December 2025, co-adwised by Bartłomiej Błaszczyszyn.
- Loic Thomassey, "Sur l'étude de mesures aléatoires issues de processus gaussiens", December 2025, adwised by Raphaël Lachièze-Rey.

PhD in progress

- Alessia Rigonat, "Modeling and AI prediction for car-sharing" since Oct 2023, advised by Christine Fricker.
- Gabriel Mastrilli, Spectral inference of spatial point processes, since September 2023, co-advised by Bartłomiej Błaszczyszyn.
- Adelie Erard, "STIT/Gibbs spatial interaction models for characterizing the effect of Land Sparing strategies", since October 2023, advised by Raphaël Lachièze-Rey.
- Paul-Pierre Rax, "Modeling of large communication networks", since Septeber 2024, advised by François Baccelli and Raphaël Lachièze-Rey.
- Philippe Sarotte, "Stochastic Models Applied to the Study of Dynamic Networks", since October 2024, advised by François Baccelli and Nahuel Soprano Loto.

- Emanuele Mengoli, "Probabilistic modeling of 6G networks", since March 2025, advised by François Baccelli and Nahuel Soprano Loto.
- Remi Bernard, "Weight dependent random connection model", since September 2025, advised by Raphaël Lachièze-Rey.
- Giacomo Salvati, "Hyperuniformity, Entropy, Rigidity and the Geometry of Gaussian Fields", since Septeber 2025, co-advised by Raphaël Lachièze-Rey.

M2 internship defended: Anna Bendo, Remi Bernard, Armand De Cacqueray, Samuel Molano-Quintana, Simon Steinlin.

11.2.2 Juries

- François Baccelli: Sandro Franceschi (jury HDR, PSL, December 2025).
- Bartłomiej Błaszczyszyn: Mohammad Taha Shah (Reviewer PhD, Indian Institute of Technology Delhi), Fabien Baeriswyl (jury PhD, Sorbonne University with University of Lausanne), Lucas Darlavoix (jury, co-adviseur PhD).
- Raphaël Lachièze-Rey: CSI (Le Comité de suivi individuel de thèse) of R. Digneaux et G. Mastrilli, jury postdoc of FSMP.

11.2.3 Educational and pedagogical outreach

- Licence:
  - Bartłomiej Błaszczyszyn (Cours) Théorie de l'information et du codage 24 heqTD, L3, ENS Paris. moodle.
  - Giacomo Salvati (Exercise sessions/TD) Analysis I for Mathematics and Physics students, University of Luxembourg (60 teaching units).
  - Philippe Sarotte (Exercise sessions/TD) Numerical Analysis, Sorbonne University (26h plus correction of copies)
- Master:
  - Bartłomiej 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,
  - Raphaël Lachièze-Rey (Cours) "Interacting Particle systems " jointly at M2 "Probabilities and Random Models", Sorbonne University and M2 "Applied and Theoretical Mathematics", University Paris-Dauphine-PSL.
  - Alessia Rigonat (Exercise classes/TD) "Introduction to probability", Sorbonne University (36h plus correction of copies).

11.3 Popularization

- Bartłomiej Błaszczyszynled a half-day session for high school students as part of the mandatory 10th-grade (*Seconde*) internship program, June 2025.

12 Scientific production

12.1 Publications of the year

International journals

[1] L. Becker, F. Baccelli and T. Taillefumier. 'Subthreshold variability of neuronal populations driven by synchronous synaptic inputs'. In: *PLoS Computational Biology* 21.10 (16th Mar. 2025). DOI: 10.1101/2025.03.16.643547. URL: https://hal.science/hal-05521676 (cit. on p. 15).

[2] C.-S. Choi and F. Baccelli. 'A Novel Analytical Model for LEO and MEO Satellite Networks based on Cox Point Processes'. In: *IEEE Transactions on Communications* 73.4 (May 2025), pp. 2265–2279. DOI: 10.1109/TCOMM.2024.3471978. URL: https://hal.science/hal-04884682. In press (cit. on p. 15).

[3] C.-S. Choi and F. Baccelli. 'Stochastic Geometry and Dynamical System Analysis of Walker Satellite Constellations'. In: *IEEE Transactions on Vehicular Technology* IEEE Explore.1-6 (11th Sept. 2026). DOI: 10.1109/TVT.2025.3608470. URL: https://hal.science/hal-05521700 (cit. on p. 15).

[4] C.-S. Choi, J. Kim and F. Baccelli. 'Analysis of a Spatially Correlated Vehicular Network Assisted by Cox-Distributed Vehicle Relays'. In: *IEEE Transactions on Vehicular Technology* 74.7 (July 2025), pp. 11221–11234. DOI: 10.1109/TVT.2025.3550181. URL: https://hal.science/hal-05521708 (cit. on p. 14).

[5] G. Fayolle and C. Fricker. 'Thermodynamical limits for models of car-sharing systems: the Autolib' example'. In: *Markov Processes And Related Fields* 31.1 (2025), pp. 55–78. URL: https://inria.hal.science/hal-04855046 (cit. on p. 13).

[6] C. Fricker and H. Mohamed. 'Mean field analysis of stochastic networks with reservation'. In: *Journal of Applied Probability* (6th Jan. 2025), pp. 1–27. DOI: 10.1017/jpr.2024.103. URL: https://hal.science/hal-03539104 (cit. on p. 10).

[7] J. Lee and F. Baccelli. 'How Much Can Reconfigurable Intelligent Surfaces Augment Sky Visibility: A Stochastic Geometry Approach'. In: *IEEE Transactions on Wireless Communications* 24.1 (2025), pp. 796–809. DOI: 10.1109/TWC.2024.3501953. URL: https://hal.science/hal-04884623 (cit. on p. 15).

[8] P. Popineau and F. Baccelli. 'On multiclass spatial birth-and-death processes with wireless-type interactions'. In: *IEEE Transactions on Information Theory* 71.9 (15th Sept. 2025), pp. 7331–7347. DOI: 10.1109/tit.2024.3392979. URL: https://hal.science/hal-04884946 (cit. on p. 12).

[9] N. Soprano-Loto, U. Ayesta, M. Jonckheere and I. M. M. Verloop. 'Decision-Epochs Matter: Unveiling Its Impact on the Stability of Scheduling With Randomly Varying Connectivity'. In: *IEEE Transactions on Networking* (2025), pp. 1–16. DOI: 10.1109/TON.2025.3585661. URL: https://hal.science/hal-05196230. In press (cit. on p. 9).

[10] N. Soprano-Loto, M. Jonckheere and P. Moyal. 'Online matching for the multiclass stochastic block model'. In: *Journal of Applied Probability* 62.4 (2025), pp. 1360–1381. URL: https://hal.science/hal-04149842 (cit. on p. 9).

[11] G. Sun, F. Baccelli, K. Feng, L. Uzeda Garcia and S. Paris. 'A Stochastic Geometry Framework for Performance Analysis of RIS-assisted OFDM Cellular Networks'. In: *IEEE Transactions on Wireless Communications* 25 (21st Oct. 2025), pp. 5859–5875. DOI: 10.1109/TWC.2025.3621323. URL: https://hal.science/hal-05521697 (cit. on p. 14).

International peer-reviewed conferences

[12] L. Darlavoix, B. Błaszczyszyn and M. K. Karray. 'Localized Statistical Learning of Cell Loads in Cellular Networks'. In: *Performance Evaluation Methodologies and Tools*. 18th EAI International Conference on Performance Evaluation Methodologies and Tools (EAI Valuetools 2025). Glasgow, United Kingdom, 2025. URL: https://hal.science/hal-05521806 (cit. on p. 12).

[13] L. Darlavoix, B. Błaszczyszyn, M. K. Karray and Z. Nehme. 'Apprentissage Statistique Cellule par Cellule de la Charge à Partir de la Demande de Trafic dans les Réseaux Cellulaires Sans Fil'. In: *CORES 2025 - 10èmes Rencontres Francophones sur la Conception de Protocoles, l'Evaluation de Performances et l'Expérimentation des Réseaux de Communication*. CORES 2025 - 10èmes Rencontres Francophones sur la Conception de Protocoles, l'Evaluation de Performances et l'Expérimentation des Réseaux de Communication. Saint Valery-sur-Somme, France, 2nd June 2025. URL: https://hal.science/hal-05030767 (cit. on pp. 12, 16).

[14] K. Feng, F. Baccelli and C. Rosenberg. 'Performance Guarantees of Cellular Networks with Hardcore Regulation and Scheduling'. In: *Proceedings IEEE Globecom 25*. IEEE Globecom 2025. Taipei, Taiwan, 8th Dec. 2025. URL: https://hal.science/hal-05521755 (cit. on p. 12).

[15] C. Fricker, H. Mohamed and A. Rigonat. 'Large-scale analysis of load-balancing policies for free-floating car-sharing models'. In: IFIP WG 7.3 Performance 2025 conference : 43rd International Symposium on Computer Performance, Modeling, Measurements and Evaluation. Amsterdam, Netherlands, 11th Nov. 2025. URL: https://hal.science/hal-05533784 (cit. on p. 13).

[16] L. Hauseux, N. Soprano-Loto and K. Avrachenkov. 'Higher-order Monte Carlo cluster dynamics for community detection in Euclidean graphs'. In: Asilomar Conference on Signals, Systems, and Computers 2025. Pacific Grove (CA), United States, 26th Oct. 2025. URL: https://inria.hal.science/hal-05267074 (cit. on p. 10).

[17] P. Sarotte, N. R. Olson, T. S. Rappaport and J. G. Andrews. 'Spectrum Coexistence Between Passive Satellites and Terrestrial Network via Chernoff Bounds'. In: IEEE ICC 2025 - IEEE International Conference on Communications. Montreal, Canada, 8th June 2025, pp. 1231–1236. DOI: 10.1109/icc52391.2025.11161076. URL: https://hal.science/hal-05523562 (cit. on p. 15).

[18] N. Soprano-Loto, U. Ayesta and I. M. M. Verloop. 'On the geometry of the stability regions of randomly modulated queuing systems'. In: *Special issue of ACM Performance Evaluation Review (PER)*. IFIP WG 7.3 Performance 2025 conference - 43rd International Symposium on Computer Performance, Modeling, Measurements and Evaluation. Amsterdam, Netherlands, 11th Nov. 2025. URL: https://hal.science/hal-05305545 (cit. on p. 10).

Doctoral dissertations and habilitation theses

[19] L. Darlavoix. 'Statistical Learning for Quality of Service Evaluation andDimensioning of Wireless Networks'. ENS-PSL, 15th Dec. 2025. URL: https://theses.hal.science/tel-05496405 (cit. on pp. 13, 22).

[20] L. Thomassey. 'On the study of some random measures obtained from Gaussian fields and point processes'. Université Paris Cité, 9th Dec. 2025. URL: https://theses.hal.science/tel-05519463 (cit. on p. 8).

Reports & preprints

[21] F. Baccelli and S. Kumar Jhawar. *On A Class Of Dynamical Poisson-Voronoi Tessellations*. 19th Nov. 2025. URL: https://inria.hal.science/hal-05519708 (cit. on p. 11).

[22] G. Fayolle and C. Fricker. *Stability and renormalization of Jackson networks with non-idling mobile servers*. Dec. 2025. URL: https://inria.hal.science/hal-05430713 (cit. on p. 14).

[23] C. Hirsch, B. Jahnel, S. K. Jhawar and P. Juhász. *Poisson approximation of fixed-degree nodes in weighted random connection models*. May 2025. DOI: 10.1016/j.spa.2025.104593. URL: https://hal.science/hal-04434459 (cit. on p. 10).

[24] C. Hirsch and R. Lachièze-Rey. *Functional central limit theorem for topological functionals of Gaussian critical points*. 15th Dec. 2025. URL: https://hal.science/hal-04787945 (cit. on p. 9).

[25] M. K. Karray, B. Blaszczyszyn and L. Darlavoix. *Data Science: From Statistics to Machine Learning and Deep Learning, with Applications to Wireless Networks*. 1st Oct. 2025. URL: https://hal.science/hal-05294023 (cit. on p. 13).

[26] R. Lachièze-Rey. *Hyperuniform random measures, transport and rigidity*. 17th Oct. 2025. URL: https://hal.science/hal-05320187 (cit. on p. 10).

[27] R. Lachièze-Rey. *Maximal rigidity of random measure and uniqueness pairs: stealthy processes, quasicrystals and periodicity*. 10th Dec. 2025. URL: https://hal.science/hal-05399897 (cit. on p. 10).

[28] R. Lachièze-Rey. *Rigidity of random stationary measures and applications to point processes*. 26th Feb. 2025. URL: https://hal.science/hal-04710645 (cit. on p. 11).

[29] S. Martineau, R. Poudevigne and P. Rax. *Stochastic domination and lifts of random variables in percolation theory*. 2025. DOI: 10.48550/arXiv.2504.02427. URL: https://hal.science/hal-05315884 (cit. on p. 11).

[30] G. Mastrilli. *Asymptotic fluctuations of smooth linear statistics of independently perturbed lattices*. 5th Mar. 2025. URL: https://hal.science/hal-04977691 (cit. on p. 9).

[31] G. Mastrilli. *Minimax estimation of the structure factor of spatial point processes*. 18th Nov. 2025. DOI: 10.48550/arXiv.2511.14551. URL: https://hal.science/hal-05520136 (cit. on p. 9).

12.2 Cited publications

[32] D. Aldous and R. Lyons. 'Processes on Unimodular Random Networks'. In: *Electronic Journal of Probability* 12 (2007), pp. 1454–1508 (cit. on p. 6).

[33] S. Athreya, W. Löhr and A. Winter. 'The gap between Gromov-vague and Gromov–Hausdorff-vague topology'. In: *Stochastic Processes and their Applications* 126.9 (2016), pp. 2527–2553 (cit. on p. 7).

[34] E. N. Gilbert. 'Random graphs'. In: *The Annals of Mathematical Statistics* 30.4 (1959), pp. 1141–1144 (cit. on p. 6).

[35] J. Illian, A. Penttinen, H. Stoyan and D. Stoyan. *Statistical analysis and modelling of spatial point patterns*. John Wiley & Sons, 2008 (cit. on p. 7).

[36] L. Kleinrock. *Communications Nets: Stochastic Message Flow and Delay*. McGraw-Hill, 1964 (cit. on p. 6).

[37] S. Mallat. *A wavelet tour of signal processing*. Elsevier, 1999 (cit. on p. 7).

[38] A. N. Rybko and S. B. Shlosman. 'Poisson hypothesis for information networks. I'. In: *Moscow mathematical journal* 5.3 (2005), pp. 679–704 (cit. on p. 6).

[39] S. Torquato. 'Hyperuniform states of matter'. In: *Physics Reports* 745 (2018), pp. 1–95 (cit. on p. 7).