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Activity Report 2019

Project-Team DYOGENE

Dynamics of Geometric Networks

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

RESEARCH CENTER
Paris

THEME
Networks and Telecommunications

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Project-Team DYOGENE

Creation of the Project-Team: 2013 July 01

Keywords:

Computer Science and Digital Science:

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A6.2.3. - Probabilistic methods
A8.1. - Discrete mathematics, combinatorics
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Other Research Topics and Application Domains:

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

1. Team, Visitors, External Collaborators

Research Scientists

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Ana Busic [Inria, Researcher]
Christine Fricker [Inria, Researcher, HDR]
Georgina Hall [Inria, Starting Research Position, until Aug 2019]
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2. Overall Objectives

2.1. Overall Objectives

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

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

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

More specifically, the scientific focus of DYOGENE defined in 2013 was on geometric network dynamics arising in communications. By geometric networks we understand networks with a nontrivial, discrete or continuous, geometric definition of the existence of links between the nodes. In stochastic geometric networks, this definition leads to random graphs or stochastic geometric models.

A first type of geometric network dynamics is the one where the nodes or the links change over time according to an exogeneous dynamics (e.g. node motion and geometric definition of the links). We will refer to this as dynamics of geometric networks below. A second type is that where links and/or nodes are fixed but harbor local dynamical systems (in our case, stemming from e.g. information theory, queuing theory, social and economic sciences). This will be called dynamics on geometric networks. A third type is that where the dynamics of the network geometry and the local dynamics interplay. Our motivations for studying these systems stem from many fields of communications where they play a central role, and in particular: message passing algorithms; epidemic algorithms; wireless networks and information theory; device to device networking; distributed content delivery; social and economic networks, power grids.

3. Research Program

3.1. Initial research axes

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

- Algorithms for network performance analysis, led by A. Bouillard and A. Busic.
- Stochastic geometry and information theory for wireless network, led by 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 2019 are summarized in the following sections.

3.2. 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].

3.3. Mathematics of wireless cellular networks

A comprehensive approach involving information theory, queueing and stochastic geometry to model and analyze the performance of large cellular networks, validated and implemented by Orange is being led by B. Blaszczyszyn in collaboration with F. Baccelli and M. K. Karray [Orange Labs]. A new collaboration between the Standardization and Research Lab at Nokia Bell Labs and ERC NEMO led by F. Baccelli has been started in 2019.

3.4. 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.

3.5. Stochastic Geometry

In collaboration with Mir-Omid Haji-Mirsadeghi [Sharif University, Tehran, Iran] and Ali Khezeli [School of Mathematical Sciences, Tehran, Iran] F. Baccelli develops a theory of unimodular random metric spaces.

The distortion properties of unconstrained one-bit compression were analyzed by F. Baccelli in collaboration with E. O'Reilly [Caltech] using high dimensional hyperplane tessellations.

In collaboration with D. Yogeshwaran [Indian Statistical Institute, Bangalore] and J. E. Yukich [Lehigh University] B. Błaszczyszyn develops a limit theory (Laws of Large Numbers and Central Limit Theorems) for functionals of spatially correlated point processes.

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.

5. Highlights of the Year

5.1. Highlights of the Year

ERC NEMO

ERC NEMO, led by F. Baccelli, started in January 2019; see 9.3.1.1.

Inria International Chair

Sean Meyn obtained Inria International Chair for the period 2019–2023 and joined Dyogene.

Markov Lecture

L. Massoulié gave the Markov Lecture at the Annual Meeting of the INFORMS society, in October in Seattle https://connect.informs.org/aps/participate46/markov.

6. New Software and Platforms

6.1. Platforms

6.1.1. CapRadio

Cellular network dimensioning toolbox *CapRadio* is being developed by Orange in a long-term collaboration between TREC/DYOGENE represented by B. Błaszczyszyn, and Orange Labs, represented by M. K. Karray. This year we are working on taking into account the “massive MIMO” in 5G cellular networks; see 8.1.1.

7. New Results

7.1. Distributed network control and smart-grids

1. Distributed Control of Thermostatically Controlled Loads: Kullback-Leibler Optimal Control in Continuous Time [20] The paper develops distributed control techniques to obtain grid services from flexible loads. The Individual Perspective Design (IPD) for local (load level) control is extended to piecewise deterministic and diffusion models for thermostatically controlled load models. The IPD design is formulated as an infinite horizon average reward optimal control problem, in which the reward function contains a term that uses relative entropy rate to model deviation from nominal dynamics. In the piecewise deterministic model, the optimal solution is obtained via the solution to an eigenfunction problem, similar to what is obtained in prior work. For a jump diffusion model this simple structure is absent. The structure for the optimal solution is obtained, which suggests an ODE technique for computation that is likely far more efficient than policy-or value-iteration.

2. Optimal Control of Dynamic Bipartite Matching Models [23] A dynamic bipartite matching model is given by a bipartite matching graph which determines the possible matchings between the various types of supply and demand items. Both supply and demand items arrive to the system according to a stochastic process. Matched pairs leave the system and the others wait in the queues, which induces a holding cost. We model this problem as a Markov Decision Process and study the discounted cost and the average cost case. We first consider a model with two types of supply and two types of demand items with an N-shaped matching graph. For linear cost function, we prove that an optimal matching policy gives priority to the end edges of the matching graph and is of threshold type for the diagonal edge. In addition, for the average cost problem, we compute the optimal threshold value. According to our numerical experiments, threshold-type policies perform also very well for more general bipartite graphs.

3. Kullback-Leibler-Quadratic Optimal Control of Flexible Power Demand [24] A new stochastic control methodology is introduced for distributed control, motivated by the goal of creating virtual energy storage from flexible electric loads, i.e. Demand Dispatch. In recent work, the authors have introduced Kullback-Leibler-Quadratic (KLQ) optimal control as a stochastic control methodology for Markovian models. This paper develops KLQ theory and demonstrates its applicability to demand dispatch. In one formulation of the design, the grid balancing authority simply broadcasts the desired tracking signal, and the heterogeneous population of loads ramps power consumption up and down to accurately track the signal. Analysis of the Lagrangian dual of the KLQ optimization problem leads to a menu of solution options, and expressions of the gradient and Hessian suitable for Monte-Carlo-based optimization. Numerical results illustrate these theoretical results.

4. Bike sharing systems: a new incentive rebalancing method based on spatial outliers detection [8] Since its launch, Velib' (the Bike Sharing System-BSS-in Paris) has emerged in the Parisian landscape and has been a model for similar systems in many cities. A major problem with BSS is the stations' heterogeneity caused by the attractivity of some stations located in particular areas. In this paper, we focus on spatial outliers defined as stations having a behavior significantly different from their neighboring stations. First, we propose an improved version of Moran scatterplot to exploit the similarity between neighbors, and we test it on a real dataset issued from Velib' system to identify outliers. Then, we design a new method that globally improves the resources' availability in bike stations by adapting the users' trips to the resources' availability. Results show that with a partial collaboration of the users or a limitation to the rush hours, the proposed method enhances significantly the resources' availability in Velib' system.

5. Stochastic Battery Operations using Deep Neural Networks [25] In this paper, we introduce a scenario-based optimal control framework to account for the forecast uncertainty in battery arbitrage problems. Due to the uncertainty of prices and variations of forecast errors, it is challenging for battery operators to design profitable strategies in electricity markets. Without any explicit assumption or model for electricity price forecasts' uncertainties, we generate future price scenarios via a data-driven, learning-based approach. By aiding the predictive control with such scenarios representing possible realizations of future markets, our proposed real-time controller seeks the optimal charge/discharge levels to maximize profits. Simulation results on a case-study of California-based batteries and prices show that our proposed method can bring higher profits for different battery parameters.

6. Aggregate capacity for TCLs providing virtual energy storage with cycling constraints [26] The coordination of thermostatically controlled loads (TCLs) is challenging due to the need to meet individual loads quality of service (QoS), such as indoor temperature constraints. Since these loads are usually on/off type, cycling rate is one of their QoS metrics; frequent cycling between on and off states is detrimental to them. While significant prior work has been done on the coordination of air conditioning TCLs, the question of cycling QoS has not been investigated in a principled manner. In this work we propose a method to characterize aggregate capacity of a collection of air conditioning TCLs that respects the loads cycling rate constraints (maximum number of cycles in a given time period). The development is done within the framework of randomized local control in which a load makes on/off decisions probabilistically. This characterization allows us to propose a reference planning problem to generate feasible reference trajectories for the ensemble that respect cycling constraints. The reference planning problem manifests itself in the form a Nonlinear Programming problem (NLP), that can be efficiently solved. Our proposed method is compared to previous methods in the literature that do not enforce aggregate cycling. Enforcing individual cycling constraint without taking that into account in reference generation leads to poor reference tracking.

7. Optimal Storage Arbitrage under Net Metering using Linear Programming [29] We formulate the optimal energy arbitrage problem for a piecewise linear cost function for energy storage devices using linear programming (LP). The LP formulation is based on the equivalent minimization of the epigraph. This formulation considers ramping and capacity constraints, charging and discharging efficiency losses of the storage, inelastic consumer load and local renewable generation in presence of net-metering which facilitates selling of energy to the grid and incentivizes consumers to install renewable generation and energy storage. We consider the case where the consumer loads, electricity prices, and renewable generations at different instances are uncertain. These uncertain quantities are predicted using an Auto-Regressive Moving Average (ARMA) model and used in a model predictive control (MPC) framework to obtain the arbitrage decision at each instance. In numerical results we present the sensitivity analysis of storage performing arbitrage with varying ramping batteries and different ratio of selling and buying price of electricity.

8. Energy Storage in Madeira, Portugal: Co-optimizing for Arbitrage, Self-Sufficiency, Peak Shaving and Energy Backup [30] Energy storage applications are explored from a prosumer (consumers with generation) perspective for the island of Madeira in Portugal. These applications could also be relevant to other power networks. We formulate a convex co-optimization problem for performing arbitrage under zero feed-in tariff, increasing self-sufficiency by increasing self-consumption of locally generated renewable energy, provide peak shaving and act as a backup power source during anticipated and scheduled power outages. Using real data from Madeira we perform short and long timescale simulations in order to select end-user contract which maximizes their gains considering storage degradation based on operational cycles. We observe energy storage ramping capability decides peak shaving potential, fast ramping batteries can significantly reduce peak demand charge. The numerical experiment indicates that storage providing backup does not significantly reduce gains performing arbitrage and peak demand shaving. Furthermore, we also use AutoRegressive Moving Average (ARMA) forecasting along with Model Predic-tive Control (MPC) for real-time implementation of the proposed optimization problem in the presence of uncertainty.

9. Sensitivity to forecast errors in energy storage arbitrage for residential consumers [34] With the massive deployment of distributed energy resources, there has been an increase in the number of end consumers that own photovoltaic panels and storage systems. The optimal use of such storage when facing Time of Use (ToU) prices is directly related to the quality of the load and generation forecasts as well as the algorithm that controls the battery. The sensitivity of such control to different forecasts techniques is studied in this paper. It is shown that good and bad forecasts can result in losses in particularly bad days. Nevertheless, it is observed that performing Model Predictive Control with a simple forecast that is representative of the pasts can be profitable under different price and battery scenarios. We use real data from Pecan Street and ToU price levels with different buying and selling price for the numerical experiments.

10. Sizing and Profitability of Energy Storage for Prosumers in Madeira, Portugal [47] This paper proposes a framework to select the best-suited battery for co-optimizing for peak demand shaving, energy arbitrage and increase self-sufficiency in the context of power network in Madeira, Portugal. Feed-in-tariff for electricity network in Madeira is zero, which implies consumers with excess production should locally consume the excess generation rather than wasting it. Further, the power network operator applies a peak power contract for consumers which imposes an upper bound on the peak power seen by the power grid interfaced by energy meter. We investigate the value of storage in Madeira, using four different types of prosumers, categorized based on the relationship between their inelastic load and renewable generation. We observe that the marginal increase in the value of storage deteriorates with increase in size and ramping capabilities. We propose the use of profit per cycle per unit of battery capacity and expected payback period as indices for selecting the best-suited storage parameters to ensure profitability. This mechanism takes into account the consumption and generation patterns, profit, storage degradation, and cycle and calendar life of the battery. We also propose the inclusion of a friction coefficient in the original co-optimization formulation to increase the value of storage by reducing the operational cycles and eliminate low returning transactions.

11. Arbitrage with Power Factor Correction using Energy Storage [48] The importance of reactive power compensation for power factor (PF) correction will significantly increase with the large-scale integration of distributed generation interfaced via inverters producing only active power. In this work, we focus on co-optimizing energy storage for performing energy arbitrage as well as local power factor corrections. The joint optimization problem is non-convex, but can be solved efficiently using a McCormick relaxation along with penalty-based schemes. Using numerical simulations on real data and realistic storage profiles, we show that energy storage can correct PF locally without reducing arbitrage gains. It is observed that active and reactive power control is largely decoupled in nature for performing arbitrage and PF correction (PFC). Furthermore, we consider a stochastic online formulation of the problem with uncertain load, renewable and pricing profiles. We develop a model predictive control based storage control policy using ARMA forecast for the uncertainty. Using numerical simulations we observe that PFC is primarily governed by the size of the converter and therefore, look-ahead in time in the online setting does not affect PFC noticeably. However, arbitrage gains are more sensitive to uncertainty for batteries with faster ramp rates compared to slow ramping batteries.

12. A Utility Optimization Approach to Network Cache Design [11] In any caching system, the admission and eviction policies determine which contents are added and removed from a cache when a miss occurs. Usually, these policies are devised so as to mitigate staleness and increase the hit probability. Nonetheless, the utility of having a high hit probability can vary across contents. This occurs, for instance, when service level agreements must be met, or if certain contents are more difficult to obtain than others. In this paper, we propose utility-driven caching, where we associate with each content a utility, which is a function of the corresponding content hit probability. We formulate optimization problems where the objectives are to maximize the sum of utilities over all contents. These problems differ according to the stringency of the cache capacity constraint. Our framework enables us to reverse engineer classical replacement policies such as LRU and FIFO, by computing the utility functions that they maximize. We also develop online algorithms that can be used by service providers to implement various caching policies based on arbitrary utility functions.

13. Rapid Mixing of Dynamic Graphs with Local Evolution Rules [15] Dynamic graphs arise naturally in many contexts. In peer-to-peer networks, for instance, a participating peer may replace an existing connection with one neighbor by a new connection with a neighbor of that neighbor. Several such local rewiring rules have been proposed to ensure that peer-to-peer networks achieve good connectivity properties (e.g. high expansion) at equilibrium. However, the question of whether there exists such a rule that converges rapidly to equilibrium has remained open. In this work, we provide an affirmative answer: we exhibit a local rewiring rule that converges to equilibrium after each participating node has undergone only a number of changes that is at most poly-logarithmic in the system size. As a byproduct, we derive new results for random walks on graphs, bounding the spread of their law throughout the transient phase, i.e. prior to mixing. These rely on an extension of Cheeger's inequality, based on generalized isoperimetric constants, and may be of independent interest.

7.2. Reinforcement learning

14. On Matrix Momentum Stochastic Approximation and Applications to Q-learning [27] Stochastic approximation (SA) algorithms are recursive techniques used to obtain the roots of functions that can be expressed as expectations of a noisy parameterized family of functions. In this paper two new SA algorithms are introduced: 1) PolSA, an extension of Polyak's momentum technique with a specially designed matrix momentum, and 2) NeSA, which can either be regarded as a variant of Nesterov's acceleration method, or a simplification of PolSA. The rates of convergence of SA algorithms is well understood. Under special conditions, the mean square error of the parameter estimates is bounded by $\sigma^2/n + o(1/n)$, where $\sigma^2 \geq 0$ is an identifiable constant. If these conditions fail, the rate is typically sub-linear. There are two well known SA algorithms that ensure a linear rate, with minimal value of variance, σ^2: the Ruppert-Polyak averaging technique, and the stochastic Newton-Raphson (SNR) algorithm. It is demonstrated here that under mild technical assumptions, the PolSA algorithm also achieves this optimality criteria. This result is established via novel coupling arguments: It is shown that the parameter estimates obtained from the PolSA algorithm couple with those of the optimal variance (but computationally more expensive) SNR algorithm, at a rate $O(1/n^2)$. The newly proposed algorithms are extended to a reinforcement learning setting to obtain new Q-learning algorithms, and numerical results confirm the coupling of PolSA and SNR.

15. Zap Q-Learning - A User's Guide [28] There are two well known Stochastic Approximation techniques that are known to have optimal rate of convergence (measured in terms of asymptotic variance): the Stochastic Newton-Raphson (SNR) algorithm (a matrix gain algorithm that resembles the deterministic Newton-Raphson method), and the Ruppert-Polyak averaging technique. This paper surveys new applications of these concepts for Q-learning: (i)The Zap Q-Learning algorithm was introduced by the authors in a NIPS 2017 paper. It is based on a variant of SNR, designed to more closely mimic its deterministic cousin. The algorithm has optimal rate of convergence under general assumptions, and showed astonishingly quick convergence in numerical examples. These algorithms are surveyed and illustrated with numerical examples. A potential difficulty in implementation of the Zap-Q-Learning algorithm is the matrix inversion required in each iteration. (ii)Remedies are proposed based on stochastic approximation variants of two general deterministic techniques: Polyak's momentum algorithms and Nesterov's acceleration technique. Provided the hyper-parameters are chosen with care, the performance of these algorithms can be comparable to the Zap algorithm, while computational complexity per iteration is far lower.

16. Zap Q-Learning With Nonlinear Function Approximation [44] The Zap stochastic approximation (SA) algorithm was introduced recently as a means to accelerate convergence in reinforcement learning algorithms. While numerical results were impressive, stability (in the sense of boundedness of parameter estimates) was established in only a few special cases. This class of algorithms is generalized in this paper, and stability is established under very general conditions. This general result can be applied to a wide range of algorithms found in reinforcement learning. Two classes are considered in this paper: (i)The natural generalization of Watkins' algorithm is not always stable in function approximation settings. Parameter estimates may diverge to infinity even in the *linear* function approximation setting with a simple finite state-action MDP. Under mild conditions, the Zap SA algorithm provides a stable algorithm, even in the case of *nonlinear* function approximation. (ii) The GQ algorithm of Maei et. al. 2010 is designed to address the stability challenge. Analysis is provided to explain why the algorithm may be very slow to converge in practice. The new Zap GQ algorithm is stable even for nonlinear function approximation.

17. Zap Q-Learning for Optimal Stopping Time Problems [43] The objective in this paper is to obtain fast converging reinforcement learning algorithms to approximate solutions to the problem of discounted cost optimal stopping in an irreducible, uniformly ergodic Markov chain, evolving on a compact subset of IR^n. We build on the dynamic programming approach taken by Tsitsikilis and Van Roy, wherein they propose a Q-learning algorithm to estimate the optimal state-action value function, which then defines an optimal stopping rule. We provide insights as to why the convergence rate of this algorithm can be slow, and propose a fast-converging alternative, the "Zap-Q-learning" algorithm, designed to achieve optimal rate of convergence. For the first time, we prove the convergence of the Zap-Q-learning algorithm under the assumption of linear function approximation setting. We use ODE analysis for the proof, and the optimal asymptotic variance property of the algorithm is reflected via fast convergence in a finance example.

7.3. Mathematics of wireless cellular networks

18. Performance analysis of cellular networks with opportunistic scheduling using queueing theory and stochastic geometry [6] Combining stochastic geometric approach with some classical results from queuing theory, in this paper we propose a comprehensive framework for the performance study of large cellular networks featuring opportunistic scheduling. Rapid and verifiable with respect to real data, our approach is particularly useful for network dimensioning and long term economic planning. It is based on a detailed network model combining an information-theoretic representation of the link layer, a queuing-theoretic representation of the users' scheduler, and a stochastic-geometric representation of the signal propagation and the network cells. It allows one to evaluate principal characteristics of the individual cells, such as loads (defined as the fraction of time the cell is not empty), the mean number of served users in the steady state, and the user throughput. A simplified Gaussian approximate model is also proposed to facilitate study of the spatial distribution of these metrics across the network. The analysis of both models requires only simulations of the point process of base stations and the shadowing field to estimate the expectations of some stochastic-geometric functionals not admitting explicit expressions. A key observation of our approach , bridging spatial and temporal analysis, relates the SINR distribution of the typical user to the load of the typical cell of the network. The former is a static characteristic of the network related to its spectral efficiency while the latter characterizes the performance of the (generalized) processor sharing queue serving the dynamic population of users of this cell.

19. Two-tier cellular networks for throughput maximization of static and mobile users [10] In small cell networks, high mobility of users results in frequent handoff and thus severely restricts the data rate for mobile users. To alleviate this problem, we propose to use heterogeneous, two-tier network structure where static users are served by both macro and micro base stations, whereas the mobile (i.e., moving) users are served only by macro base stations having larger cells; the idea is to prevent frequent data outage for mobile users due to handoff. We use the classical two-tier Poisson network model with different transmit powers, assume independent Poisson process of static users and doubly stochastic Poisson process of mobile users moving at a constant speed along infinite straight lines generated by a Poisson line process. Using stochastic geometry, we calculate the average downlink data rate of the typical static and mobile (i.e., moving) users, the latter accounted for handoff outage periods. We consider also the average throughput of these two types of users defined as their average data rates divided by the mean total number of users co-served by the same base station. We find that if the density of a homogeneous network and/or the speed of mobile users is high, it is advantageous to let the mobile users connect only to some optimal fraction of BSs to reduce the frequency of handoffs during which the connection is not assured. If a heterogeneous structure of the network is allowed, one can further jointly optimize the mean throughput of mobile and static users by appropriately tuning the powers of micro and macro base stations subject to some aggregate power constraint ensuring unchanged mean data rates of static users via the network equivalence property.

20. Location Aware Opportunistic Bandwidth Sharing between Static and Mobile Users with Stochastic Learning in Cellular Networks [9] We consider location-dependent opportunistic bandwidth sharing between static and mobile downlink users in a cellular network. Each cell has some fixed number of static users. Mobile users enter the cell, move inside the cell for some time and then leave the cell. In order to provide higher data rate to mobile users, we propose to provide higher bandwidth to the mobile users at favourable times and locations, and provide higher bandwidth to the static users in other times. We formulate the problem as a long run average reward Markov decision process (MDP) where the per-step reward is a linear combination of instantaneous data volumes received by static and mobile users, and find the optimal policy. The transition structure of this MDP is not known in general. To alleviate this issue, we propose a learning algorithm based on single timescale stochastic approximation. Also, noting that the unconstrained MDP can be used to solve a constrained problem, we provide a learning algorithm based on multi-timescale stochastic approximation. The results are extended to address the issue of fair bandwidth sharing between the two classes of users. Numerical results demonstrate performance improvement by our scheme, and also the trade-off between performance gain and fairness.

21. Per-Link Reliability and Rate Control: Two Facets of the SIR Meta Distribution [13] The meta distribution (MD) of the signal-to-interference ratio (SIR) provides fine-grained reliability performance in wireless networks modeled by point processes. In particular, for an ergodic point process, the SIR MD yields the distribution of the per-link reliability for a target SIR. Here we reveal that the SIR MD has a second important application, which is rate control. Specifically, we calculate the distribution of the SIR threshold (equivalently, the distribution of the transmission rate) that guarantees each link a target reliability and show its connection to the distribution of the per-link reliability. This connection also permits an approximate calculation of the SIR MD when only partial (local) information about the underlying point process is available.

22. Simple Approximations of the SIR Meta Distribution in General Cellular Networks [14] Compared to the standard success (coverage) probability , the meta distribution of the signal-to-interference ratio (SIR) provides much more fine-grained information about the network performance. We consider general heterogeneous cellular networks (HCNs) with base station tiers modeled by arbitrary stationary and ergodic non-Poisson point processes. The exact analysis of non-Poisson network models is notoriously difficult, even in terms of the standard success probability, let alone the meta distribution. Hence we propose a simple approach to approximate the SIR meta distribution for non-Poisson networks based on the ASAPPP ("approximate SIR analysis based on the Poisson point process") method. We prove that the asymptotic horizontal gap G_0 between its standard success probability and that for the Poisson point process exactly characterizes the gap between the bth moment of the conditional success probability, as the SIR threshold goes to 0. The gap G_0 allows two simple approximations of the meta distribution for general HCNs: 1) the per-tier approximation by applying the shift G_0 to each tier and 2) the effective gain approximation by directly shifting the meta distribution for the homogeneous independent Poisson network. Given the generality of the model considered and the fine-grained nature of the meta distribution, these approximations work surprisingly well.

23. Interference Queueing Networks [16] This work features networks of coupled processor sharing queues in the Euclidean space, where customers arrive according to independent Poisson point processes at every queue, are served, and then leave the network. The coupling is through service rates. In any given queue, this rate is inversely proportional the interference seen by this queue, which is determined by the load in neighboring queues, attenuated by some distance-based path-loss function. The main focus is on the infinite grid network and translation invariant path-loss case. The model is a discrete version of a spatial birth and death process where customers arrive to the Euclidean space according to Poisson rain and leave it when they have transferred an exponential file, assuming that the instantaneous rate of each transfer is determined through information theory by the signal to interference and noise ratio experienced by the user. The stability condition is identified. The minimal stationary regime is built using coupling from the past techniques. The mean queue size of this minimal stationary regime is determined in closed form using the rate conservation principle of Palm calculus. When the stability condition holds, for all bounded initial conditions, there is weak convergence to this minimal stationary regime; however, there exist translation invariant initial conditions for which all queue sizes converge to infinity.

24. Statistical learning of geometric characteristics of wireless networks [19] Motivated by the prediction of cell loads in cellular networks, we formulate the following new, fundamental problem of statistical learning of geometric marks of point processes: An unknown marking function, depending on the geometry of point patterns, produces characteristics (marks) of the points. One aims at learning this function from the examples of marked point patterns in order to predict the marks of new point patterns. To approximate (interpolate) the marking function, in our baseline approach, we build a statistical regression model of the marks with respect some local point distance representation. In a more advanced approach, we use a global data representation via the scattering moments of random measures, which build informative and stable to deformations data representation, already proven useful in image analysis and related application domains. In this case, the regression of the scattering moments of the marked point patterns with respect to the non-marked ones is combined with the numerical solution of the inverse problem, where the marks are recovered from the estimated scattering moments. Considering some simple, generic marks, often appearing in the modeling of wireless networks, such as the shot-noise values, nearest neighbour distance, and some characteristics of the Voronoi cells, we show that the scattering moments can capture similar geometry information as the baseline approach, and can reach even better performance, especially for non-local marking functions. Our results motivate further development of statistical learning tools for stochastic geometry and analysis of wireless networks, in particular to predict cell loads in cellular networks from the locations of base stations and traffic demand.

25. Determinantal thinning of point processes with network learning applications [21] A new type of dependent thinning for point processes in continuous space is proposed, which leverages the advantages of determinantal point processes defined on finite spaces and, as such, is particularly amenable to statistical, numerical, and simulation techniques. It gives a new point process that can serve as a network model exhibiting repulsion. The properties and functions of the new point process, such as moment measures, the Laplace functional, the void probabilities, as well as conditional (Palm) characteristics can be estimated accurately by simulating the underlying (non-thinned) point process, which can be taken, for example, to be Poisson. This is in contrast (and preference to) finite Gibbs point processes, which, instead of thinning, require weighting the Poisson realizations, involving usually intractable normalizing constants. Models based on determinantal point processes are also well suited for statistical (supervised) learning techniques, allowing the models to be fitted to observed network patterns with some particular geometric properties. We illustrate this approach by imitating with determinantal thinning the well-known Matérn II hard-core thinning, as well as a soft-core thinning depending on nearest-neighbour triangles. These two examples demonstrate how the proposed approach can lead to new, statistically optimized, probabilistic transmission scheduling schemes.

26. Analyzing LoRa long-range, low-power, wide-area networks using stochastic geometry [22] In this paper we present a simple, stochastic-geometric model of a wireless access network exploiting the LoRA (Long Range) protocol, which is a non-expensive technology allowing for long-range, single-hop connectivity for the Internet of Things. We assume a space-time Poisson model of packets transmitted by LoRA nodes to a fixed base station. Following previous studies of the impact of interference, we assume that a given packet is successfully received when no interfering packet arrives with similar power before the given packet payload phase. This is as a consequence of LoRa using different transmission rates for different link budgets (transmissions with smaller received powers use larger spreading factors) and LoRa intra-technology interference treatment. Using our model, we study the scaling of the packet reception probabilities per link budget as a function of the spatial density of nodes and their rate of transmissions. We consider both the parameter values recommended by the LoRa provider, as well as proposing LoRa tuning to improve the equality of performance for all link budgets. We also consider spatially non-homogeneous distributions of LoRa nodes. We show also how a fair comparison to non-slotted Aloha can be made within the same framework.

27. Reliability and Local Delay in Wireless Networks: Does Bandwidth Partitioning Help? [33] In a series of papers initiated through a collaboration with Nokia Bell Labs, we study the effect of bandwidth partitioning (BWP) on the reliability and delay performance in infrastructureless wireless networks. The reliability performance is characterized by the density of concurrent transmissions that satisfy a certain reliability (outage) constraint and the delay performance by so-called local delay, defined as the average number of time slots required to successfully transmit a packet. We concentrate on the ultrareliable regime where the target outage probability is close to 0. BWP has two conflicting effects: while the interference is reduced as the concurrent transmissions are divided over multiple frequency bands, the signal-to-interference ratio (SIR) requirement is increased due to smaller allocated bandwidth if the data rate is to be kept constant. Instead, if the SIR requirement is to be kept the same, BWP reduces the data rate and in turn increases the local delay. For these two approaches with adaptive and fixed SIR requirements, we derive closed-form expressions of the local delay and the maximum density of reliable transmissions in the ultrareliable regime. Our analysis shows that, in the ultrareliable regime, BWP leads to the reliability-delay tradeoff.

28. The Influence of Canyon Shadowing on Device-to-Device Connectivity in Urban Scenario [35] In this work, we use percolation theory to study the feasibility of large-scale connectivity of relay-augmented device-to-device (D2D) networks in an urban scenario, featuring a haphazard system of streets and canyon shadowing allowing only for line-of-sight (LOS) communications in a limited finite range. We use a homogeneous Poisson-Voronoi tessellation (PVT) model of streets with homogeneous Poisson users (devices) on its edges and independent Bernoulli relays on the vertices. Using this model, we demonstrated the existence of a minimal threshold for relays below which large-scale connectivity of the network is not possible, regardless of all other network parameters. Through simulations, we estimated this threshold to 71.3%. Moreover, if the mean street length is not larger than some threshold (predicted to 74.3% of the communication range; which might be the case in a typical urban scenario) then any (whatever small) density of users can be compensated by equipping more crossroads with relays. Above this latter threshold, good connectivity requires some minimal density of users, compensated by the relays in a way we make explicit. The existence of the above regimes brings interesting qualitative arguments to the discussion on the possible D2D deployment scenarios.

29. Relay-assisted Device-to-Device Networks: Connectivity and Uberization Opportunities [46] It has been shown that deploying device-to-device (D2D) networks in urban environments requires equipping a considerable proportion of crossroads with relays. This represents a necessary economic investment for an operator. In this work, we tackle the problem of the economic feasibility of such relay-assisted D2D networks. First, we propose a stochastic model taking into account a positive surface for streets and crossroads, thus allowing for a more realistic estimation of the minimal number of needed relays. Secondly, we introduce a cost model for the deployment of relays, allowing one to study operators' D2D deployment strategies. We investigate the example of an uberizing neo-operator willing to set up a network entirely relying on D2D and show that a return on the initial investment in relays is possible in a realistic period of time, even if the network is funded by a very low revenue per D2D user. Our results bring quantitative arguments to the discussion on possible uberization scenarios of telecommunications networks.

30. Continuum Line-of-Sight Percolation on Poisson-Voronoi Tessellations [45] 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 of these two processes, two points of 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.

7.4. High-dimensional statistical inference

31. Discrete Mean Field Games: Existence of Equilibria and Convergence [12] We consider mean field games with discrete state spaces (called discrete mean field games in the following) and we analyze these games in continuous and discrete time, over finite as well as infinite time horizons. We prove the existence of a mean field equilibrium assuming continuity of the cost and of the drift. These conditions are more general than the existing papers studying finite state space mean field games. Besides, we also study the convergence of the equilibria of N -player games to mean field equilibria in our four settings. On the one hand, we define a class of strategies in which any sequence of equilibria of the finite games converges weakly to a mean field equilibrium when the number of players goes to infinity. On the other hand, we exhibit equilibria outside this class that do not converge to mean field equilibria and for which the value of the game does not converge. In discrete time this non-convergence phenomenon implies that the Folk theorem does not scale to the mean field limit.

32. Modularity-based Sparse Soft Graph Clustering [32] Clustering is a central problem in machine learning for which graph-based approaches have proven their efficiency. In this paper, we study a relaxation of the modularity maxi-mization problem, well-known in the graph partitioning literature. A solution of this relaxation gives to each element of the dataset a probability to belong to a given cluster, whereas a solution of the standard modularity problem is a partition. We introduce an efficient optimization algorithm to solve this relaxation, that is both memory efficient and local. Furthermore, we prove that our method includes, as a special case, the Louvain optimization scheme, a state-of-the-art technique to solve the traditional modularity problem. Experiments on both synthetic and real-world data illustrate that our approach provides meaningful information on various types of data.

33. Phase Transitions, Optimal Errors and Optimality of Message-Passing in Generalized Linear Models [41] We consider generalized linear models where an unknown n-dimensional signal vector is observed through the successive application of a random matrix and a non-linear (possibly probabilistic) componentwise function. We consider the models in the high-dimensional limit, where the observation consists of m points, and $m/n \to \alpha$ where α stays finite in the limit $m, n \to \infty$. This situation is ubiquitous in applications ranging from supervised machine learning to signal processing. A substantial amount of work suggests that both the inference and learning tasks in these problems have sharp intrinsic limitations when the available data become too scarce or too noisy. Here, we provide rigorous asymptotic predictions for these thresholds through the proof of a simple expression for the mutual information between the observations and the signal. Thanks to this expression we also obtain as a consequence the optimal value of the generalization error in many statistical learning models of interest, such as the teacher-student binary perceptron, and introduce several new models with remarquable properties. We compute these thresholds (or "phase transitions") using ideas from statistical physics that are turned into rigorous methods thanks to a new powerful smart-path interpolation technique called the stochastic interpolation method, which has recently been introduced by two of the authors. Moreover we show that a polynomial-time algorithm refered to as generalized approximate message-passing reaches the optimal generalization performance for a large set of parameters in these problems. Our results clarify the difficulties and challenges one has to face when solving complex high-dimensional statistical problems.

34. Efficient inference in stochastic block models with vertex labels [18] We study the stochastic block model with two communities where vertices contain side information in the form of a vertex label. These vertex labels may have arbitrary label distributions, depending on the community memberships. We analyze a version of the popular belief propagation algorithm. We show that this algorithm achieves the highest accuracy possible whenever a certain function of the network parameters has a unique fixed point. When this function has multiple fixed points, the belief propagation algorithm may not perform optimally, where we conjecture that a non-polynomial time algorithm may perform better than BP. We show that increasing the information in the vertex labels may reduce the number of fixed points and hence lead to optimality of belief propagation.

35. Planting trees in graphs, and finding them back [36] In this paper we study detection and reconstruction of planted structures in Erdős-Rényi random graphs. Motivated by a problem of communication security, we focus on planted structures that consist in a tree graph. For planted line graphs, we establish the following phase diagram. In a low density region where the average degree λ of the initial graph is below some critical value $\lambda_c = 1$, detection and reconstruction go from impossible to easy as the line length K crosses some critical value $f(\lambda)\ln(n)$, where n is the number of nodes in the graph. In the high density region $\lambda > \lambda_c$, detection goes from impossible to easy as K goes from $o(\sqrt{n})$ to $\omega(\sqrt{n})$, and reconstruction remains impossible so long as $K = o(n)$. For D-ary trees of varying depth h and $2 \leq D \leq O(1)$, we identify a low-density region $\lambda < \lambda_D$, such that the following holds. There is a threshold $h* = g(D)\ln(\ln(n))$ with the following properties. Detection goes from feasible to impossible as h crosses $h*$. We also show that only partial reconstruction is feasible at best for $h \geq h*$. We conjecture a similar picture to hold for D-ary trees as for lines in the high-density region $\lambda > \lambda_D$, but confirm only the following part of this picture: Detection is easy for D-ary trees of size $\omega(\sqrt{n})$, while at best only partial reconstruction is feasible for D-ary trees of any size $o(n)$. These results are in contrast with the corresponding picture for detection and reconstruction of *low rank* planted structures, such as dense subgraphs and block communities: We observe a discrepancy between detection and reconstruction, the latter being impossible for a wide range of parameters where detection is easy. This property does not hold for previously studied low rank planted structures.

36. Robustness of spectral methods for community detection [37] This work is concerned with community detection. Specifically, we consider a random graph drawn according to the stochastic block model: its vertex set is partitioned into blocks, or communities, and edges are placed randomly and independently of each other with probability depending only on the communities of their two endpoints. In this context, our aim is to recover the community labels better than by random guess, based only on the observation of the graph.

In the sparse case, where edge probabilities are in $O(1/n)$, we introduce a new spectral method based on the distance matrix D, where $D_{ij} = 1$ iff the graph distance between i and j, noted $d(i,j)$ is equal to ℓ. We show that when $\ell \sim c\log(n)$ for carefully chosen c, the eigenvectors associated to the largest eigenvalues of D provide enough information to perform non-trivial community recovery with high probability, provided we are above the so-called Kesten-Stigum threshold. This yields an efficient algorithm for community detection, since computation of the matrix D can be done in $O(n^{1+\kappa})$ operations for a small constant κ.

We then study the sensitivity of the eigendecomposition of D when we allow an adversarial perturbation of the edges of G. We show that when the considered perturbation does not affect more than $O(n^{\varepsilon})$ vertices for some small $\varepsilon > 0$, the highest eigenvalues and their corresponding eigenvectors incur negligible perturbations, which allows us to still perform efficient recovery.

Our proposed spectral method therefore: i) is robust to larger perturbations than prior spectral methods, while semi-definite programming (or SDP) methods can tolerate yet larger perturbations; ii) achieves non-trivial detection down to the KS threshold, which is conjectured to be optimal and is beyond reach of existing SDP approaches; iii) is faster than SDP approaches.

7.5. Distributed optimization for machine learning

37. Optimal Convergence Rates for Convex Distributed Optimization in Networks [17] This work proposes a theoretical analysis of distributed optimization of convex functions using a network of computing units. We investigate this problem under two communication schemes (centralized and decentralized) and four classical regularity assumptions: Lipschitz continuity, strong convexity, smoothness, and a combination of strong convexity and smoothness. Under the decentralized communication scheme, we provide matching upper and lower bounds of complexity along with algorithms achieving this rate up to logarithmic constants. For non-smooth objective functions, while the dominant term of the error is in $O(1/\sqrt{t})$, the structure of the communication network only impacts a second-order term in $O(1/t)$, where tt is time. In other words, the error due to limits in communication resources decreases at a fast rate even in the case of non-strongly convex objective functions. Such a convergence rate is achieved by the novel multi-step primal-dual (MSPD) algorithm. Under the centralized communication scheme, we show that the naive distribution of standard optimization algorithms is optimal for smooth objective functions, and provide a simple yet efficient algorithm called distributed randomized smoothing (DRS) based on a local smoothing of the objective function for non-smooth functions. We then show that DRS is within a $d^{1/4}$ multiplicative factor of the optimal convergence rate, where d is the underlying dimension.

38. Accelerated Decentralized Optimization with Local Updates for Smooth and Strongly Convex Objectives [31] In this paper, we study the problem of minimizing a sum of smooth and strongly convex functions split over the nodes of a network in a decentralized fashion. We propose the algorithm $ESDACD$, a decentralized accelerated algorithm that only requires local synchrony. Its rate depends on the condition number κ of the local functions as well as the network topology and delays. Under mild assumptions on the topology of the graph, $ESDACD$ takes a time $O((\tau_{\max} + \Delta_{\max})\sqrt{\kappa/\gamma}\ln(\epsilon^{-1}))$ to reach a precision ϵ where γ is the spectral gap of the graph, $\tau_{\max}$ the maximum communication delay and $\Delta_{\max}$ the maximum computation time. Therefore, it matches the rate of $SSDA$, which is optimal when $\tau_{\max} = \Omega\left(\Delta_{\max}\right)$. Applying $ESDACD$ to quadratic local functions leads to an accelerated randomized gossip algorithm of rate $O(\sqrt{\theta_{\text{gossip}}/n})$ where θ_{gossip} is the rate of the standard randomized gossip. To the best of our knowledge, it is the first asynchronous gossip algorithm with a provably improved rate of convergence of the second moment of the error. We illustrate these results with experiments in idealized settings.

39. An Accelerated Decentralized Stochastic Proximal Algorithm for Finite Sums [49] Modern large-scale finite-sum optimization relies on two key aspects: distribution and stochastic updates. For smooth and strongly convex problems, existing decentralized algorithms are slower than modern accelerated variance-reduced stochastic algorithms when run on a single machine, and are therefore not efficient. Centralized algorithms are fast, but their scaling is limited by global aggregation steps that result in communication bottlenecks. In this work, we propose an efficient **A**ccelerated, **D**ecentralized stochastic algorithm for **F**inite**S**ums named ADFS, which uses local stochastic proximal updates and randomized pairwise communications between nodes. On machines, ADFS learns from samples in the same time it takes optimal algorithms to learn from samples on one machine. This scaling holds until a critical network size is reached, which depends on communication delays, on the number of samples , and on the network topology. We provide a theoretical analysis based on a novel augmented graph approach combined with a precise evaluation of synchronization times and an extension of the accelerated proximal coordinate gradient algorithm to arbitrary sampling. We illustrate the improvement of ADFS over state-of-the-art decentralized approaches with experiments.

7.6. Stochastic Geometry

40. On the Dimension of Unimodular Discrete Spaces, Part I: Definitions and Basic Properties [39] This work introduces 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 is presented for the analysis of these dimensions. In particular, analogues of Billingsley's lemma and Frostman's lemma are presented. These lemmas are instrumental in deriving upper bounds on dimensions, whereas lower bounds are obtained from specific coverings. The notions of unimodular Hausdorff measure and unimodular dimension function are also introduced. This toolbox is used to connect the unimodular dimensions to various other notions such as growth rate, scaling limits, discrete dimension and amenability. 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.

41. On the Dimension of Unimodular Discrete Spaces, Part II: Relations with Growth Rate [40] The notions of unimodular Minkowski and Hausdorff dimensions are defined in [39] for unimodular random discrete metric spaces. This work is focused on the connections between these notions and the polynomial growth rate of the underlying space. It is shown that bounding the dimension is closely related to finding suitable equivariant weight functions (i.e., measures) on the underlying discrete space. The main results are unimodular versions of the mass distribution principle and Billingsley's lemma, which allow one to derive upper bounds on the unimodular Hausdorff dimension from the growth rate of suitable equivariant weight functions. Also, a unimodular version of Frostman's lemma is provided, which shows that the upper bound given by the unimodular Billingsley lemma is sharp. These results allow one to compute or bound both types of unimodular dimensions in a large set of examples in the theory of point processes, unimodular random graphs, and self-similarity. Further results of independent interest are also presented, like a version of the max-flow min-cut theorem for unimodular one-ended trees.

42. Doeblin trees [4] This work is centered on the random graph generated by a Doeblin-type coupling of discrete time processes on a countable state space whereby when two paths meet, they merge. This random graph is studied through a novel subgraph, called a bridge graph, generated by paths started in a fixed state at any time. The bridge graph is made into a unimodular network by marking it and selecting a root in a specified fashion. The unimodularity of this network is leveraged to discern global properties of the larger Doeblin graph. Bi-recurrence, i.e., recurrence both forwards and backwards in time, is introduced and shown to be a key property in uniquely distinguishing paths in the Doeblin graph, and also a decisive property for Markov chains indexed by $\mathbb{Z}$. Properties related to simulating the bridge graph are also studied.

43. The Stochastic Geometry of Unconstrained One-Bit Compression [5] A stationary stochastic geometric model is proposed for analyzing the data compression method used in one-bit compressed sensing. The data set is an unconstrained stationary set, for instance all of $\mathbb{R}^n$ or a stationary Poisson point process in $\mathbb{R}^n$. It is compressed using a stationary and isotropic Poisson hyperplane tessellation, assumed independent of the data. That is, each data point is compressed using one bit with respect to each hyperplane, which is the side of the hyperplane it lies on. This model allows one to determine how the intensity of the hyperplanes must scale with the dimension n to ensure sufficient separation of different data by the hyperplanes as well as sufficient proximity of the data compressed together. The results have direct implications in compressed sensing and in source coding.

44. Limit theory for geometric statistics of point processes having fast decay of correlations [7] We develop a limit theory (Laws of Large Numbers and Central Limit Theorems) for functionals of spatially correlated point processes. The "strength" of data correlation is captured and controlled by the speed of decay of the additive error in the asymptotic factorization the correlation functions, when the separation distance increases. In this way, the classical theory of Poisson and Bernoulli processes is extended to a larger class of data inputs, such as determinantal point processes with fast decreasing kernels, including the α-Ginibre ensembles, permanental point processes as well as the zero set of Gaussian entire functions. Both linear (U-statistics) and non-linear geometric statistics (such as clique counts, the number of Morse critical points, intrinsic volumes of the Boolean model, and total edge length of the k-nearest neighbor graph) are considered.

7.7. Information theory

45. Error Exponents for MAC Channelss [3] This work analyzes a class of Multiple Access Channels (MAC) where the sum of the dimensions of the transmitted signals matches that of the received signal. This channel is a classical object of information theory in the power constrained case. We first focus on the Poltyrev regime, namely the case without power constraint. Using point process techniques, we derive the capacity under general stationarity and ergodicity noise assumptions as well as a representation of the error probability.

We use this to derive bounds on the error exponent in the Gaussian case. This also leads to new results on the power constrained error exponents.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. CRE with Orange

Two year contract titled *Taking into account the "massive MIMO" in the assessment of QoS and the dimensioning of 5G cellular networks* between Inria and Orange Labs started 2018. It is a part of a long-term collaboration between TREC/DYOGENE, represented by B. Błaszczyszyn and Orange Labs, represented by M. K. Karray on the development of analytic tools and methods allowing one to capture macroscopic relation between antennas roll-out, frequency allocation, volume of traffic carried on the network and quality of service parameters such as the average and the variation of bandwidth available to end users. This work addresses crucial technical and economical issues related to the operator core business, particularly related to the current evolution of the cellular network technology (4G⇒5G). The developed solutions are implemented by Orange Labs in the internal toolbox *CapRadio* (see 6.1.1) and used by the Direction of Regulatory Affairs of Orange.

8.1.2. Contract with EDF

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

8.1.3. CIFRE with Orange

Contract with Orange started in 2017 and continued in 2018 for the co-advising by B. Błaszczyszyn of a PhD student of Orange, Quentin Le Gall.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Laboratory of Information, Networking and Communication Sciences (LINCS)

Dyogene participates in LINCS https://www.lincs.fr, a research centre co-founded by Inria, Institut Mines-Télécom, UPMC and Alcatel-Lucent Bell Labs (currently Nokia Bell Labs) dedicated to research and innovation in the domains of future information and communication networks, systems and services.

9.1.2. PGMO

Dyogene participates in the PGMO (Gaspard Monge Program for Optimization, operations research, and their interactions with data science) via the project a 2 year project "Distributed control of flexible loads" funded through the ICODE/IROE call. This is a collaborative project between University Paris-Sud (PI: Gilles Stoltz) and Inria (PI: Ana Busic).

9.2. National Initiatives

9.2.1. GdR GeoSto

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

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

9.2.2. GdR RO

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

9.2.3. 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.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. NEMO

NEMO, NEtwork MOtion https://cordis.europa.eu/project/id/788851, https://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. In March 2019, an inaugural workshop *Processus ponctuels et graphes aléatoires unimodulaires* https://project.inria.fr/ercnemo/fr/presentation was organized at Inria Paris.

9.3.2. Collaborations with Major European Organizations

Partner: VITO (Belgium); https://vito.be/en.

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

9.4. International Initiatives

9.4.1. Inria International Partners

9.4.1.1. Informal International Partners

- University of Florida; Collaborations with Prof Sean Meyn (ECE), Associate Prof Prabir Barooah (MAE), and the PhD students: A. Devraj (ECE), A. Coffman (MAE), N. Cammardella (ECE), J. Mathias (ECE).

- Sharif University, Tehran; Collaborations with O. Mirsadeghi.
- UC Berkeley; Collaborations with V. Anantharam.
- Indian Statistical Institute (ISI), Bangalore; Collaborations with Yogeshwaran D.

9.4.2. Participation in Other International Programs

9.4.2.1. Indo-French Center of Applied Mathematics

IFCAM Project "Geometric statistics of stationary point processes" B. Błaszczyszyn and Yogeshwaran D. from Indian Statistical Institute (ISI), Bangalore, have got in 2018 the approval from Indo-French Centre for Applied Mathematics (IFCAM), for their joint project on "Geometric statistics of stationary point processes" for the period 2018–2021. Yogeshwaran D. was visiting Dyogene for two weeks in March and November 2019.

9.4.2.2. Microsoft Research-Inria collaboration

Microsoft Research-Inria collaboration: Laurent Massoulié heads the Microsoft Research-Inria Joint Centre, and also participates to the "Distributed Machine Learning" project of the Joint Centre, together with Francis Bach (Inria), Sébastien Bubeck and Lin Xiao (MSR Redmond), and PhD student Hadrien Hendrikx.

9.4.2.3. Inria International Chairs

IIC- MEYN Sean

Title: Distributed Control and Smart Grid

International Partner (Institution - Laboratory - Researcher):

University of Florida (United States) - Department of Electrical and Computer Engineering - Sean Meyn

Duration: 2019 – 2023

Start year: 2019

See also: https://www.inria.fr/sites/default/files/2019-12/HoldersChairesInt_EN.pdf

TOPIC: "Distributed Control and Smart Grid"

9.5. International Research Visitors

9.5.1. Visits of International Scientists

- Ali Khezeli [School of Mathematical Sciences, Tehran, Iran],
- Christian Hirsch [Bernoulli Institute, University of Groningen,
- David Métivier [Los Alamos National Laboratory, USA]
- Deepjyoti Deka [Los Alamos National Laboratory, USA]
- Guenter Last [Karlsruhe Institute of Technology, Germany],
- Hermann Thorisson [University of Islande],
- Holger Keeler [University of Melbourne, Australia] ,
- Hrvoje Pandžić [University of Zagreb, Croatia]
- Itai Benjamini [Weizmann Institute of Science, Rehovot, Israel],
- Joe Yukich [Lehigh University, Bethelem, PA, USA],
- Josu Doncel [University of the Basque Country, Spain],
- Lucas Pereira [Técnico Lisboa, Portugal]
- Miklós Abért [MTA Renyi Institute, Budapest, Hungary],
- Mir-Omid Haji-Mirsadeghi [Sharif University, Tehran, Iran],
- Natasa Dragovic [The University of Texas at Austin, TX, USA],

- Nelson Antunes [University of Faro, Portugal],
- Venkatachalam Anantharam [University of California, Berkeley, CA USA],
- Yogeshwaran D. [ISI, Bangalore, India],

9.5.1.1. Internships

- Bastien Dubail [École Normale Supérieure de Lyon],
- Emmanuel Kravitzch [Inria],
- Erwan Pichon [Inria].
- Ge Jin [Inria],
- Maxence Lefort [Inria].

9.5.2. Visits to International Teams

- C. Fricker: University of Faro, Portugal (one week).

9.5.2.1. Research Stays Abroad

- A.Busic: program participant (5 weeks in total) of "The mathematics of energy systems", Isaac Newton Institute for Mathematical Sciences, Cambridge, UK. Spring 2019, https://www.newton.ac.uk/event/mes

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

In collaboration with M. Vojnovic (London School of Economics), A. Busic and L. Massoulié organized an international workshop on Machine Learning and User Decision Making https://ml-udm.github.io/ at the ENS on May 23-24, 2019.

10.1.1.1. Member of the Organizing Committees

Members of Dyogene (co-)organized the following events:

- ERC inaugural workshop *Processus ponctuels et graphes aléatoires unimodulaires* https://project.inria.fr/ercnemo/fr/presentation/,
- Scientific session *Modélisation et analyse des systèmes de vélo-partage* at RFTM2019 (2emes Rencontres Francophones Transport et Mobilité, 11-13/06/2019 Montréal); https://symposia.cirrelt.ca/RFTM2019/
- A. Busic: co-lead (with E. Hyon, LIP 6) of the research group COSMOS (Stochastic optimization and control, modeling and simulation) of the GDR-RO; http://gdrro.lip6.fr/?q=node/78. Includes scientific organization of a one-day workshops per year (approx. 50 participants); In 2019: 8th GDT COSMOS workshop: "Stochastic Optimization and Reinforcement Learning"; November 2019; http://gdrro.lip6.fr/?q=node/211
- A. Busic: one week workshop "Flexible operation and advanced control for energy systems" within INI Cambridge program "The mathematics of energy systems", January 2019, Cambridge, UK, https://www.newton.ac.uk/event/mesw01

10.1.2. Journal

10.1.2.1. Reviewer - Reviewing Activities

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

10.1.3. Invited Talks

- Mathematics Colloquium at *Paris-Descartes*, November 2019, F. Baccelli (talk on high dimensional stochastic geometry);
- Mathematics Colloquium at *Karlsruhe Institute of Technology*, July 2019, F. Baccelli (talk on unimodular dimensions);
- Invited lecture at the workshop *Modern Applied Probability, in celebration of Sergey Foss' 65th birthday*, ICMS, Edinburgh, May 2019 F. Baccelli (talk on particle systems); https://www.icms.org.uk/sergey65.php
- Invited lecture at the workshop *Point processes in space, time, and beyond*, Aalborg University, May 2019 F. Baccelli (talk on random graphs); http://people.math.aau.dk/~rw/PointSpaceBeyond/
- Mathematics Colloquium at *Institut Elie Cartan de Lorraine*, April 2019 F. Baccelli (on unimodular random metric spaces);
- Colloquium at **CEA LETI**, Grenoble, January 2019, F. Baccelli (talk on wireless stochastic geometry);
- Training School on Machine Learning for Communications, ISEP, Paris, B. Błaszczyszyn; https://sites.google.com/view/mlc-training-school/
- "STAR workshop on random graphs", Groningen Netherlands, B. Błaszczyszyn; http://www.math.rug.nl/~hansen/STAR2019/
- invited talk in the Department of Statistics and Data Science Yale University, September 2019, M. Lelarge;
- Isaac Newton Institute for Mathematical Sciences, Cambridge, UK, April 2019, A. Busic (on grid balancing through distributed control of flexible loads) ; video: https://www.newton.ac.uk/seminar/20190502143015301
- Simons Institute, UC Berkeley, June 2019, A. Busic (on optimizing mean-field dynamics for distributed control of flexible loads)
- Journées Scientifiques Inria, Lyon, June 2019, A. Busic (Optimisation/contrôle dans des réseaux électriques)
- CWI – Inria workshop, September 2019, Ana Busic (Optimizing mean-field dynamics for flexible loads control in power systems)
- CMAP seminar, École Politechnique, December 2019, A. Busic (on optimal control in dynamic matching systems)

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 S. Samain (TD) Structures et algorithmes aléatoires 60heqTD, L3, ENS Paris.
- Licence: L. Massoulié (Cours) Social and Communication networks 60heqTD, L3, l'X.
- Master: B. Błaszczyszyn (Cours) Processus ponctuels, graphes aléatoires et géeométrie stochastique 39heqTD, M2 Probabilités et Modèles Aléatoires, UPMC.
- Master: A. Busic (Cours) and L. Stephan (TD) Modèles et algorithmes de réseaux 60heqTD, M1, ENS Paris.
- Master: A. Busic (Cours) Fondements de la modélisation des réseaux 18 heqTD, M2 MPRI.
- Master: M. Lelarge (Cours) Deep Learning Do it Yourself, M1, ENS Paris. X, X-HEC https://mlelarge.github.io/dataflowr-web/

- Master: M. Lelarge (Cours) Deep Learning Do it Yourself, M1, ENS Paris.
- Master: L. Massoulié (Cours) Inference in large random graphs, M2 Université d'Orsay.
- Summer school: M. Lelarge (Cours) HANDS-ON TOUR TO DEEP LEARNING WITH PYTORCH, https://mlelarge.github.io/dataflowr-web/cea_edf_inria.html.
- Invited mini-course: L. Massoulié at Journée spéciale Stat Math 2019 of Société Française de Statistiques, Institut Henri Poincaré.

10.2.2. Supervision

- PhD: Léo Miolane, "High dimensional statistics", defended in 2019, advised by M. Lelarge. [2]
- PhD: Md Umar Hashmi, "Decentralized control for renewable integration in smartgrids", defended in 2019, advised by A. Busic. [1]
- PhD in progress: Alexis Galland, Deep Learning on Graphs, since 2017, advised by M. Lelarge.
- PhD in progress: Quentin Le Gall "Crowd networking : modélisation de la connectivité D2D" since October 2017; PhD CIFRE co-advised by B. Błaszczyszyn and E. Cali (Orange).
- PhD in progress: Antoine Brochard "Signal processing for point processes and statistical learning for telecommunications", since September 2018; PhD CIFRE co-advised by B. Błaszczyszyn and Georgios Paschos (Huawei).
- PhD in progress: Sébastien Samain, "Monte Carlo methods for performance evaluation and reinforcement learning", since November 2016, advised by A. Busic,
- PhD in progress: Arnaud Cadas, "Dynamic matching models", since October 2017, supervised by A. Busic.
- PhD in progress: Michel Davydov, since September 2019, F. Baccelli.
- PhD in progress: Luca Ganassali, since September 2019.
- PhD in progress: Hadrien Hendrikx, since 2019
- PhD in progress: Sayeh Khaniha, form 2019, supervised by F. Baccelli.
- PhD in progress: Edouard Pineau, since 2019,
- PhD in progress: Bharath Roy, since 2019, supervised by F. Baccelli and B. Błaszczyszyn,
- PhD in progress: Ilia Shilov, since 2019, supervised by A. Busic,
- PhD in progress: Ludovic Stephan, since 2019.

10.2.3. Juries

- F. Baccelli: PhD reviewer of **Gourab GHATAK**, Télécom Paris; HDR reviewer of **Marios KOUNTOURIS**, Université Paris-Sud 1; HDR jury member of **Raphaël LACHIEZE-REY**, Université Paris-Descartes.
- B. Blaszczyszyn: PhD reviewer of: **Sanjoy Kumar JHAWAR**, Indian Institute of Science Bangalore, India; **Arnaud POINAS**, Université de Rennes 1; HDR reviewer of: **Marious KOUNTOURIS**, Université Paris-Sud 1; PhD jury member of : **Jalal RACHAD**, Télécom Paris.
- C. Fricker: PhD reviewer of: **Celine COMTE**, Université Paris-Saclay; PhD jury member of: **Hamza BEN AMMAR**, Université de Rennes 1.
- M. Lelarge: PhD jury member Xiaoyi MAI, Université Paris-Saclay.

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[1] M. U. HASHMI. *Optimization and Control of Storage in Smart Grids*, PSL Research University, December 2019, https://tel.archives-ouvertes.fr/tel-02462786

[2] L. MIOLANE. *Fundamental limits of inference: A statistical physics approach*, Ecole normale supérieure - ENS PARIS ; Inria Paris, June 2019, https://hal.archives-ouvertes.fr/tel-02446988

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