NETWORKS

NETWORKS is a project of University of Amsterdam, Eindhoven University of Technology, Leiden University and Center for Mathematics and Computer Science (CWI) and receives funding from OC&W through NWO

THENETWORKCENTER.NL

ANNUAL REPORT 2022

2022 was the year the world reopened. While during the first months of 2022 The Netherlands was still in a lockdown, gradually all COVID-19 related measures were lifted. The pandemic had a huge impact on our private and professional lives, and we were happy that we slowly got back to the usual modes of scientific interaction: in-person meetings, blackboard sessions to discuss ideas, non-virtual workshops and conferences, and research visits.

We do observe that the pandemic has done a lot of harm. Senior researchers definitely experienced significant negative effects, but junior staff members (PhD students, postdocs) suffered considerably more. A typical PhD student concentrates on a single project, sometimes making great progress, but quite often essentially stuck. In order to deal with the frustrations that are inherent to doing research, it very much helps when the student sees other students going through the same process. Doing research on their own, often in a far-from-ideal student apartment, can become a painful experience. I wish to use this opportunity to compliment our junior staff members on the way they coped with these challenges. At the four nodes of NETWORKS, we have been very alert to potential problems in terms of morale or mental health, and have been generous in terms of granting contract extensions.

Academically, 2022 was a year with many highlights. Despite the fact that we are slowly entering the program's last phase, there are still many exciting new initiatives. In 2020 we were awarded a COFUND grant for PhD students, and a year later another COFUND grant for postdocs. Through these European grants, totaling over 3 M€, we have doubled the remaining number of NETWORKS PhD and postdoc positions. We have started a set of new projects, some on themes already covered within NETWORKS, and others on topics that connect us with other disciplines. In general, we can say that since the start of the program, back in 2014, we have become much broader, for instance also covering research lines that connect us with the social sciences. The Match Makers Event, connecting NETWORKS members with researchers from the social sciences, is held twice a year, with a growing participation from a broad range of disciplines. Gradually, the connections between the involved mathematical disciplines have significantly deepened as well.

The set of projects with industrial partners grows steadily as well. In this context we mention a few of our fruitful interactions. With the Rotterdam-based company Transtrend we study advanced opinion dynamics models, to be used in the context of the spread of price information through a network. With the Dutch semi-public research institute TNO we work on projects on advanced wireless networks and large-scale transportation networks. With the Dutch mail and parcel delivery company PostNL we are involved in a project on the optimization of delivery time intervals, as announced to customers. These projects illustrate how the abstract findings of the NETWORKS program trickle down into concrete applications.

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Like in previous years, we have had impressive scientific output, resulting in a large number of impactful publications in the leading journals in probability theory, combinatorics, operations research, and algorithmics. NETWORKS has played a key role in the organization of international conferences and workshops, such as the meeting on "Graph Limits, Nonparametric Models, and Estimation" at the Simons Institute (Berkeley) and the virtual “Data-driven Queueing Challenges” event (jointly with ACEMS from Australia and the Turing Institute). Another highlight is the theme meeting for a broad audience, held at the beautiful location of the Kamerlingh Onnes building in Leiden, with a focus on networks and fake news.

This annual report provides an overview of the NETWORKS activities in 2022. Additional information can be found on our website (www.thenetworkcenter.nl) and on the Network Pages (networkpages.nl).

Michel Mandjes, project leader
Marieke Kranenburg, project manager

RESEARCH THEMES

THEME 1: APPROXIMATE AND EXACT NETWORK METHODS

The design, optimization, and control of networks lead to a large variety of challenging algorithmic problems. Unfortunately, many of these problems are NP-hard, which means that there are no efficient algorithms that solve these problems optimally on all possible instances. Nevertheless, NP-hard network problems need to be dealt with in practice. One approach to is to develop approximation algorithms, which are guaranteed to compute solutions that are very close to an optimal solution. Another approach is to exploit the fact that not all input instances are equally hard: some instances enjoy structural properties that make it possible to compute an optimal solution in an efficient manner. In Theme 1 we explore these and other approaches to algorithmic network problems.

HIGHLIGHTS

- A paradigm shift occurred very recently in online optimization: instead of assuming no prior knowledge about future requests, predictions on them are given, e.g. through machine learning. However, simply trusting such predictions might lead to poor solutions. This opened a vibrant line of research that aims at incorporating error-prone predictions into online algorithms. The goal is to have a performance close to that of an optimal offline algorithm when given accurate predictions, and never being much worse than the best known algorithm without access to predictions. Further, the performance should degrade gracefully with increasing prediction error. A crucial ingredient in this line of research is an appropriate prediction error measure. Leen Stougie (CWI), Michelle Sweering (CWI), and co-workers defined a universal error measure for input predictions for metric graph problems. They applied it to obtain strong new results for the online traveling salesman problem with predictions and improved results for the online Steiner tree problem with predictions.

- Frits Spieksma (TU/e), together with Bart Smeulders (TU/e), Valentin Bartier (Grenoble Alpes), and Yves Crama (Liege) studied an important and very complex issue linked to the optimization of transplant matchings in kidney exchange programs, namely, the inherent uncertainty in the assessment of compatibility between donors and recipients of transplants. Although this issue has previously received some attention in the optimization literature, most attempts to date have focused on applying recourse to solutions selected within restricted spaces. Spieksma and co-workers explicitly formulated the maximization of the expected number of transplants as a two-stage stochastic integer programming problem. The formulation turns out to be computationally difficulty, both from a theoretical and from a numerical perspective. Different algorithmic approaches are proposed and tested experimentally for its solution. The quality of the kidney exchanges produced by these algorithms compares favorably with that of earlier models.

- In the multi-robot patrolling problem, one wants to schedule the movements of k surveillance robots so that together they patrol a given network. The goal is that each node of the network is visited infinitively often, while minimizing the maximum time between any two consecutive visits of any node. When k=1 (a single robot), then it is optimal to make the robot repeatedly traverse a minimum-length tour that visits all nodes. Thus, for k=1, the problem is equivalent to the famous Trav-

eling Salesman Problem, which is NP-hard. Mark de Berg (TU/e) and co-workers study the even more challenging version where $k \geq 2$. They presented an efficient algorithm to approximate an optimal cyclic solution. For $k=2$, they proved that an optimal cyclic solution is, in fact, an overall optimal solution, and for $k>2$ they proved that an optimal cyclic solution is a 2(1-1/k) approximation of the overall optimal solution.

THEME 2: SPATIAL NETWORKS

In many applications the networks under consideration are embedded in space, leading to geometric networks. Examples are railway networks, where nodes correspond to stations and edges to railway tracks, and large molecules, where nodes correspond to atoms and edges to chemical bonds. In many real-world networks the geometry is an important feature that is hard to treat mathematically. Typically, connections between nearby nodes are more abundant than connections between distant nodes, yet long-range connections play a crucial role in the small-world behavior these networks exhibit, i.e., all vertices are connected via short connecting chains. In addition, a high variability in the degrees of the nodes is observed. A key spatial stochastic model is percolation, while a well-known algorithmic problem where geometry plays a key role is the Euclidean traveling salesman problem.

HIGHLIGHTS

- Henk Alkema, Mark de Berg, Morteza Monemizadeh, and Leonidas Theocharous (all TU/e) investigated the classic Euclidean Traveling Salesman Problem. This problem has been studied extensively in a setting where the points to be visited are points in the plane (or some higher dimensional space) and the salesman can move in a straight line between any two points. A natural setting is where the points to be visited lie inside a polygonal environment, which restricts the movement of the salesman. Surprisingly, this setting was not studied before. It is challenging because, unlike the classic Euclidean Traveling Salesman Problem, the underlying metric does not have bounded doubling dimension. Nevertheless, Alkema and co-workers managed to present a subexponential exact algorithm for it, whose running time is optimal under the Exponential-Time Hypothesis.

- Remco van der Hofstad, Pim van der Hoorn, and Neeladri Maitra (all TU/e) investigated the local limit of a broad spectrum of spatial inhomogeneous random graphs, including hyperbolic random graphs. Such models have recently been proposed for models with inhomogeneous degree distributions and high clustering. The local limit describes various local properties of these models, including their clustering, but also their degree-degree dependencies. Further, it gives a suggestion about what the size of the giant should be. This suggestion was proved to be correct for various models, relying on estimates that had appeared previously, in a recent paper by van der Hofstad called “The giant in random graphs is almost local”. Here, it is crucial to note that without the local limit, it would not have been possible to identify the law of large numbers for the giant.

THEME 3: QUANTUM NETWORKS

Quantum computers are the next generation computing devices. They hold a tremendous promise to revolutionize the way we process

and handle information throughout science, technology, and our rapidly evolving information society. Quantum computers can be used to implement quantum algorithms, which in many instances are able to perform computations much faster than classical algorithms. This year saw significant developments in the national organization, public awareness, outreach, and government support for quantum technology in the Netherlands (see developments outside of NETWORKS below).

HIGHLIGHTS

- In "On Converses to the Polynomial Method", Jop Briët and Francisco Escudero Gutiérrez (CWI) gave new and stronger counterexamples to a question of Ambainis et al. concerning the relationship between quantum query algorithms and low-degree polynomials. This work was accepted to and presented at the 17th Conference on the Theory of Quantum Computation, Communication and Cryptography (TQC 2022) at the University of Chicago at Urbana Champaign.

- In "A recursive Lovász theta number for simplex-avoiding sets", Davi Castro-Silva (CWI), Fernando Maria de Oliveira Filho (TU Delft), Lucas Slot (CWI), and Frank Vallentin (Köln) extend the Lovász theta number to geometric hypergraphs on the unit sphere and on Euclidean space and obtain an upper bound for the independence ratio of these hypergraphs. This work was published in the Proceedings of the American Mathematical Society (2022).

DEVELOPMENTS OUTSIDE OF NETWORKS

In April, the two 2021 Abel Prize winners László Lovász and Avi Wigderson gave in-person presentations at two NETWORKS-sponsored events at CWI and KNAW to celebrate their achievements. The 2022 Breakthrough prize was awarded to four pioneers of quantum computing and quantum information theory: Charles Bennett, Gilles Brassard, David Deutsch, and Peter Shor. Two events were organized in November to celebrate this wonderful news, a special edition of the QuSoft seminar at CWI and a day at the KNAW in Amsterdam. Both Bennett and Brassard gave in-person lectures.

THEME 4: DYNAMICS OF NETWORKS

Networks typically evolve over time. The way in which this happens is often closely related to their functionality. Random graphs are essential tools to model real-life network structures as stochastic objects that grow in time according to certain local growth rules. By adapting these rules, different types of dynamic network behavior can be captured and analyzed.

HIGHLIGHTS

- Alessandro Garavaglia (TU/e), Rajat Hazra (UL), Remco van der Hofstad (TU/e) and CO-FUND PhD student Rounak Ray (TU/e) investigated the local limit of preferential attachment models with random out-degrees, significantly extending previous work. Interestingly, for power-law out-degrees, the various degree distributions in the graph display surprising power-law behavior, where the various degree power-law exponents depend in a sensitive way on the power-law exponent of the out-degrees and the preferential attachment mechanism.

- Peter Braunsteins (UvA), Frank den Hollander (UL), and Michel Mandjes (UvA) concluded work on a dynamic version of the Erdös-Rényi random graph. Each edge switches on and off at certain rates, independently of the other edges. A sample-path large deviation principle for

dynamic Erdös-Rényi random graphs was developed, thus extending the seminal Chatterjee/Varadhan paper. This large deviation principle was then used to identify the most likely path the dynamic graph takes to obtain an atypically large number of triangles, and the most likely path between two given graphs. The dynamics exhibit a broad range of possible patterns, notably covering phenomena that are not present in the static case.

- In a follow-up project, the same authors considered a class of graph-valued stochastic processes in which each vertex has a type that fluctuates randomly over time. Collectively, up to a given time, the paths of the vertex types determine the probabilities that the edges are active or inactive at that time. In the scaling considered, fluctuations in the graph-valued process are more likely to be caused by fluctuations in the vertex types than by fluctuations in the states of the edges given these types. The results are in terms of sample-path large deviation principles and convergence of stochastic processes. The underlying model has the flexibility to treat a class of stochastic processes where the edge probabilities depend not only on the fluctuations in the vertex types but also on the state of the graph itself.

- Luca Avena (UL), with Paolo Milanesi (Marseille), Alexandre Gaudillière (Marseille), and Matteo Quattropani (UL) studied the geometry of a parametric random spanning rooted forest measure on a complete graph with and without community structures. This forest measure generalizes the classical uniform spanning tree measure, and can be sampled by means of so-called Wilson's algorithm based on dynamic properties of loop-erased random walks on the graph of interest. On a complete graph with and without communities, the asymptotic random emergent partition is characterized by studying two-point correlations.

THEME 5: DYNAMICS ON NETWORKS

In past years, extensive research worldwide has led to new results for processes that evolve on static networks, such as flow of information, disease, traffic, or energy. In contrast, the understanding of processes on dynamic networks, themselves evolving over time, is still in its infancy and is presently limited to a handful of instructive examples. Since double dynamics are prevalent in most real-world networks, there is an urgent need for breakthroughs. Particularly challenging is the setting of co-evolution, where the network dynamics not only influence the processes evolving on the network, but also vice versa. This leads to a complex two-way feedback interaction, which poses huge mathematical challenges.

HIGHLIGHT

MARTIJN GÖSGENS SELECTED AS ONE OF THE FACES OF SCIENCE

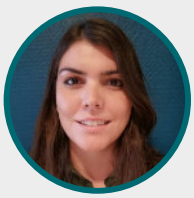
Every year, 12 PhD candidates are selected to be Faces of Science by the KNAW, the Young Academy, and NEMO Kennislink. In their work as Faces of Science, they focus on science communication with the aim to give youngsters who are about to choose a course of study an idea of what it is like to be a scientist. In 2022, NETWORKS PhD candidate Martijn Gösgens was selected. As a member of Faces of Science, Martijn has his personal blog where he regularly posts short articles (in Dutch). With his blog, Martijn wants to give a glimpse into his everyday life and research as a young scientist. One of his blogs is about Netsweeper: a network variant of the classic game Minesweeper developed by Martijn.

HIGHLIGHTS

- Oliver Nagy, Luca Avena, Frank den Hollander (all UL), and Remco van der Hofstad (TU/e) analyzed the mixing profile of a random walk on a dynamic random permutation, focusing on the regime where the walk evolves much faster than the permutation. Two types of dynamics generated by random transpositions were considered: one allows for coagulation of permutation cycles only, the other allows for both coagulation and fragmentation. It was shown that for both types, in the limit of the length of the permutation tending to infinity and after an appropriate scaling of time, the total variation distance between the current distribution and the uniform distribution drops down in a single jump. This jump, which is similar to a one-sided cut-off, occurs after a random time whose distribution can be computed explicitly, and goes from the value 1 to a value that is a strictly decreasing and computable deterministic function of the time of the jump. After the jump, the total variation distance follows this function down to 0. This type of random mixing profile is rare.

- Benedikt Meylahn and Michel Mandjes, together with Arnoud den Boer (all UvA), studied the problem of an agent continuously faced with the decision of placing trust or not placing trust in an institution. Each agent in each round sees the response of the institution, but there is also communication between the agents. The agents make use of Bayesian learning in order to estimate the institution's true trustworthiness and make the decision to place trust based on myopic rationality. It is concluded that, for different modes of communication between the agents, a pair of agents has a larger chance of learning the true trustworthiness of an institution than a single agent. Communication between agents promotes the formation of long-term trust with a trustworthy institution, as well as the timely exit from a trust relationship with an untrustworthy institution.

NEW PERSONNEL



Dr. Elene Anton Balerdi
Postdoc, TU/e

Shreehari Bodas, MSc
PhD student, UvA

Marianne de Bruin
Support Staff, TU/e

Dr. Davi Castro Silva
Postdoc, CWI

Dr. Benoît Corsini
Postdoc, TU/e

Dr. Martin Frohn
Postdoc, TU/e

Dr. Royi Jacobovic
Postdoc, UvA

Agnieszka Janicka, MSc
PhD student, TU/e

Dr. Ross Kang
Associate professor, UvA

Dr. Matteo Quattropani
Postdoc, UL

Sten Wessel, MSc
PhD student, TU/e

Dr. Wiktor Zuba
Postdoc, CWI

- Luca Avena, Rangel Baldasso, Rajat Hazra, Frank den Hollander, and Matteo Quattropani (all UL) studied the classical two-opinion dynamics known as the voter model on a random regular graph. It was known that consensus is achieved on a time scale that is linear in the number of vertices, and that on this time scale the density of one of the two opinions can be described via a Wright-Fisher diffusion. The evolution of the density of discordant edges (edges whose vertices have different opinions) was analyzed. This led to new insights into how the system evolve before the linear time scale. In particular, it was found that the density of discordant edges undergoes a non-trivial quasi-stationary evolution.

- Martin Frohn and Frits Spieksma (TU/e) looked at network design in phylogenetics from a new information theory perspective. Recent advances on the combinatorics of the Balanced Minimum Evolution Problem (BMEP) have shown that statistically consistent estimation models in phylogenetics are closely related to a class of cross-entropy minimization problems. Broadening this understanding to network design problems beyond phylogenetics may radically change current perspectives on the computational aspects of seemingly unrelated problems, and lead to more effective approximate and exact solution algorithms. The aim of the project was to explore the combinatorial and optimizational aspects of selected network design problems that share characteristics associated with the BMEP (in particular, connections between information theory, augmentation, and routing problems), and to exploit the insights to derive new integer linear programming formulations that are able to solve instances of practical use. Specifically, the target was to identify similarities in problems defined on distinct types of networks to specify general notions like permuto-associa-hedra for different polytopes of network design problems.

THEME 6: TRANSPORTATION AND TRAFFIC NETWORKS

Transportation and traffic networks are prominent examples of highly complex networks. Virtually all sectors of society are facing issues regarding their design, operations, performance, and control. In this NETWORKS theme, in some projects the network structure is fixed and focus is on the effect of the randomness involved in user behavior, whereas in others the main objective concerns shaping of the network structure.

HIGHLIGHTS

- Nikki Levering and Michel Mandjes (UvA) studied a stochastic network model for road traffic, in which traffic velocities depend on the state of a continuous-time Markovian random environment. This model is able to capture the impact of both random traffic events (e.g., incidents) and more deterministic traffic patterns (e.g., rush hours), on the driveable speeds in the network. In a first project, together with Marko Boon (TU/e), they illustrated how to fit (inter-)incident times and the corresponding driveable speeds, so as to operationalize such a stochastic travel-time model. Specifically, data from both Nationaal Dataportaal Wegverkeer and Rijkswaterstaat was used to estimate travel-time distributions in the Dutch highway network. In a second project, together with Rens Kamphuis (UvA), computationally efficient algorithms were devised that use individual link travel-time distributions to determine a driver's optimal departure time: the latest time

of departure such that a certain on-time arrival probability can be guaranteed. Considering that traffic conditions may change between the time of request and the advised time of departure, the study focused on the online version of this problem as well.

- Rens Kamphuis (UvA), Michel Mandjes (UvA), and Paulo Serra (VU) developed an estimator for travel times in a road traffic network with spatial dependence, using probe vehicle data. In such networks, new information about the travel time distribution becomes available when travelling to the destination. They show that their estimator is maximally precise given the information available. Moreover, numerical experiments illustrate that the estimation procedure, in combination with state-of-the-art routing strategies, can lead to substantial gains in the driver's objective function.

- Tim Engels, together with Ivo Adan, Onno Boxma, and Jacques Resing (all TU/e), analyzed the picking time of orders in warehouses. In a short paper published in Operations Research Letters, the order picking time distribution has been derived exactly for a wide range of storage policies. With these results, one can optimize the storage and layout design of warehouses with respect to a number of performance measures, e.g. mean and variance. In a second report (work in progress), the mean and variance of the order picking time are analyzed, resulting in exact expressions for general order size distributions. These results are used to approximate the waiting time in several queueing models, giving more insights in the effect of warehousing design.

- Purva Joshi, Marko Boon, and Sem Borst (all TU/e) analyzed an intersection-based platoon-forming framework for heterogeneous autonomous traffic. In this framework, the intersection access dynamics are captured via a queueing model (or, more specifically, a polling model) with multiple customer types, and vehicle trajectories leading up to the intersection are accounted for by a joint optimization procedure. The focus is on deriving computationally fast and interpretable closed-form expressions for safe and efficient vehicle trajectories during the process of platoon formation, and to show that these closed-form trajectories are equivalent to those obtained via the joint optimization procedure. Additionally, they conducted a nume-

PHD DEFENCES

PHD STUDENT	DEFENCE DATE	UNIVERSITY	THESIS TITLE	PROMOTORES
Farrokh Labib	26 January 2022	UvA / CWI	Statistical inverse problems for population processes	Harry Buhrman, Jop Briët
Fabian Stroh	6 April 2022	UvA	Hamilton cycles and algorithms	Joanna Ellis-Monaghan, Viresh Patel
Ruben Brokkelkamp	21 September 2022	UvA / CWI	How close does it get? From Near-Optimal Network Algorithms to Suboptimal Equilibrium Outcomes	Guido Schäfer, Ulle Endriss

rical study to obtain approximations for the capacity of an intersection under the platoon-forming framework.

THEME 7: COMMUNICATION AND ENERGY NETWORKS

Communication and energy networks are both prominent instances of highly complex large-scale networked systems which are of critical importance to society. Because of their vital interest, these systems need to be designed to achieve consistently high levels of performance and reliability, and yet be cost-effective to operate. This involves huge challenges, especially since both communication and energy networks are subject to inherent uncertainty and random variation in demand as well as supply.

HIGHLIGHTS

- Youri Raaijmakers, who obtained his PhD in December 2021 at TU/e, completed a joint paper with his supervisors Sem Borst and Onno Boxma on fork-join and redundancy systems with heavy-tailed job sizes (to appear in Queueing Systems, 2023). He investigated the tail asymptotics of the response time distribution in several settings that are relevant when generating and processing big data sets with parallel algorithms in clusters. In particular, he proved how many replicas are sufficient to achieve the optimal asymptotic tail behavior of the response time.

- Behind the backdrop of high computational demand posed by deep learning, as well as fundamental hardware restrictions for classical computing units, research is devoted to alternative computing architecture. This includes technologies such as optimal computing, which promises benefits like low power consumption, small latency, broad bandwidth and natural parallelism. To make good on these promises, several challenges must be overcome first, especially for new, so-called Optical Neural Networks (ONNs). One of these issues concerns noise in analog photonic implementations. To combat noise in ONNs, Gianluca Kosmella, Ripalta Stabile, and Jaron Sanders (all TU/e) studied ONN designs that reduce noise. One of the designs also allowed them to establish mathematically that ONNs have the same expressive power as regular neural networks. The other design is aimed at improving the performance of ONNs in a practical setting where resources are generally limited.

- Diego Goldsztajn, Sem Borst (both TU/e), and Johan van Leeuwaarden (Tilburg) studied load-balancing algorithms for systems of heterogeneous server pools. Their work has applications in the context of data centers and cloud computing platforms supporting video streaming and online gaming, where the level of congestion has a significant impact on the experience of users. They derived an upper bound for the quality-of-service that a system can provide, and characterized the ideal distribution of the tasks across the server pools that achieves this upper bound. While in the homogeneous setting it is optimal to have the same number of tasks at each of the server pools, in the heterogeneous case the optimal distribution of the load depends intricately on the computing power of each server pool and the level of demand. They also provided two load balancing policies that asymptotically achieve the optimal performance, one of which is a computationally multi-threshold policy that can be efficiently deployed in large-scale systems with an unknown demand.

PUBLICATION HIGHLIGHTS

- **TSP in a Simple Polygon** Alkema, H., Berg, M. D., Monemizadeh, M. & Theocharous, L., *30th Annual European Symposium on Algorithms, ESA 2022*, pp 5:1–5:14, 2022
- **Linking the mixing times of random walks on static and dynamic random graphs** Avena L., Güldas H., Hofstad R. van der, Hollander F. den & Nagy O., *Stochastic Processes and their Applications 153*, pp 145–182, 2022
- **A Token-Based Central Queue with Order-Independent Service Rates** Ayesta, U., Bodas, T., Dorsman, J. L., & Verloop, I. M., *Operations Research, 70(1)*, pp 545–561, 2022
- **Crossover times in bipartite networks with activity constraints and time-varying switching rates** Borst, S.C., den Hollander, W.T.F., Nardi, F., Taati, S., *The Annals of Applied Probability 32(6)*, p 4279–4314, 2022
- **On converses to the polynomial method** Briët, J, & Escudero Gutiérrez, F., *17th Conference on the Theory of Quantum Computation, Communication and Cryptography (TQC 2022), LIPIcs (232)[6]* pp 6:1—6:10, 2022
- **A recursive Lovász theta number for simplex-avoiding sets** Castro-Silva, D, De Oliveira, FM, Slot, L., Vallentin, F., *Proceedings of the American Mathematical Society 150(8): 3307–3322*, 2022
- **Large Deviation Principle for the Maximal Eigenvalue of Inhomogeneous Erdős–Rényi Random Graphs** Chakrabarty A., Hazra R.S., Hollander W.T.F. den, Sfragara M., *Journal of Theoretical Probability 35*, pp 2413–2441, 2022
- **Preprocessing for Outerplanar Vertex Deletion: An Elementary Kernel of Quartic Size** Donkers, H., Jansen, B. M. P. & Włodarczyk, M., *Algorithmica 84 (11)*, pp 3407–3458, 2022
- **Self-learning threshold-based load balancing** Goldsztajn, D., Borst, S. C., van Leeuwaarden, J. S. H., Mukherjee, D. & Whiting, P. A., *INFORMS Journal on Computing. 34(1)*, pp 39–54, 2022
- **The Parabolic Anderson Model on a Galton-Watson tree revisited** den Hollander, F and Wang, D, *Journal of Statistical Physics 189(1)*, 2022
- **A framework for efficient dynamic routing under stochastically varying conditions** Levering, N. A. C., Boon, M. A. A., Mandjes, M. R. H., & Nunez Queija, R., *Transportation Research. Part B: Methodological 160*, pp 97–124, 2022
- **Achievability stability in redundancy systems** Raaijmakers, Y. & Borst, S.C., *Proceedings of the ACM on Measurement and Analysis of Computing Systems 4 (3)*, pp 1–21, 2022
- **Recourse in Kidney Exchange Programs** Smeulders, B. M. L., Bartier, V., Crama, Y. & Spieksma, F. C. R., *INFORMS Journal on Computing 34 (2)*, pp 1191–1206, 2022
- **Efficient evaluation of stochastic traffic flow models using Gaussian process approximation** Storm, P.J., Mandjes, M.R.H., van Arem, B., *Transportation Research Part B Methodological 164(4):126–144*, 2022

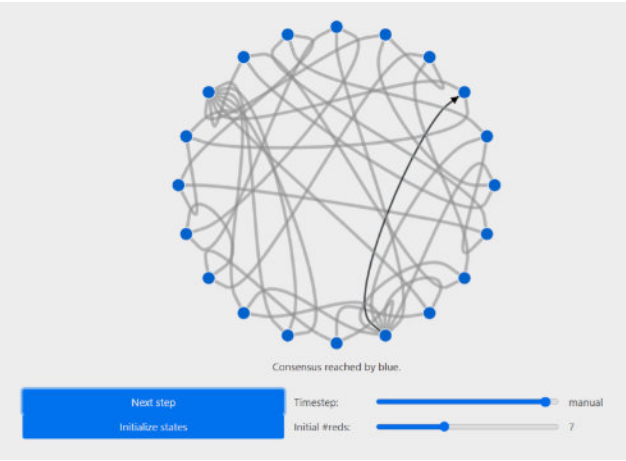
PORTFOLIOS

NETWORK PAGES

The Network Pages are an interactive web portal aimed at a broad audience interested in network science. While much of the content is produced by members of the NETWORKS project, we welcome contributions from everyone. We provide an incentive for authors in the form of interactive demos that can help to enliven written contributions.

During 2022 we managed to maintain a constant publication rate of one article per week. The number of subscribed members of the Network Pages increased by 33 members to 105. Our LinkedIn and Twitter accounts have 353 and 140 followers, respectively. Throughout 2022 we had a constant traffic of 1000 unique visitors per month.

Martijn Gösgens, who is a PhD student at the TU/e, worked on animations for the Network Pages. In 2022, two interactive animations were developed.



An interactive animation showing how the Voter Model works. Developed by Martijn Gösgens for an article written by Federico Capannoli.

KNOWLEDGE UTILIZATION

The research activities in NETWORKS are not only driven by intriguing scientific quests, but also strongly inspired by urgent challenges involving complex dynamic networks that industry and society are increasingly being confronted with. Several paths are pursued to accomplish the transfer of novel insights and results and translate fundamental concepts into actual implementations. Specifically, the main vehicles for knowledge transfer and utilization are the training of young talented people within the program through internships, collaboration with other scientific disciplines, companies and societal organizations, and outreach to primary and secondary schools and the general public (see also the Network Pages).

There is successful collaboration with TNO. The deployment of drone-mounted base stations offers an agile and cost-efficient way to sustain coverage and/or provide capacity relief in wireless networks in case of crowded events or emergency scenarios. The optimal deployment and positioning of drone base stations involves however significant challenges. Motivated by this issue, Tom Pijnappel (TU/e), Hans van den Berg (UT & TNO), Sem Borst (TU/e), and Remco Litjens (TNO) developed an analytical method based on multi-class loss systems to estimate the blocking and coverage probabilities for drone-assisted cellular networks. Since this method requires only information that is readily available to network operators, it can be used to determine the minimum required number of drones and their corresponding locations for a given target performance level.

There is growing interest in mathematical models describing the dynamics of opinions of individuals in a population. The main goal is to better understand phenomena such

as consensus forming and polarization, in particular, the way in which these depend on the underlying network structure. While most existing models represent an individual's opinion via a value on a fixed opinion interval, Michel Mandjes, in a joint project with Robert Duivenvoorden and Danny Chan (Transtrend) and Andreas Flache (RUG), has proposed an alternative modeling framework, in which an interpretation is assigned only to the relative positions of opinions with respect to each other. The resulting mechanism is rich enough to cover the full spectrum of relevant dynamic patterns, while remaining computationally straightforward.

Han Zhou finished his PhD project, which was carried out in the framework of a partnership between TNO and UvA. The focus was on quantitative modelling of new mobility modes in large-scale traffic networks. Zhou managed to set up sophisticated simulation modules that are capable of soundly evaluating the behavior of huge populations of travellers.

Roshan Mahes works on the development of strategies for parcel delivery, in the context of a collaboration between the mathematics department of UvA, the UvA business school (ABS) and the Dutch mail service provider PostNL. Mahes has in particular analyzed the benefits of schedule updates using online delivery data.

MATCHMAKERS SEMINARS

The NETWORKS Matchmakers seminars continued in 2022. The aim is to bring together researchers from social sciences, economic sciences, mathematics, and computer science sharing an interest in complex networks, with the aim to discover valuable synergies. To reach a larger public than only the NETWORKS community, a separate website and newsletter have been set up, see www.networksmatchmaking.nl.

Two seminars took place in 2022. During the first one (25 March 2022, online), presentations were given by Saeed Badri, Bernd Heidergott, and Ines Lindner (all Tinbergen institute) about the interrelated dynamics of social networks and infectious disease spread, and by Mike Lees (UvA) entitled “Computational Models to understand School Segregation: the role of social networks in parents and children”. The second seminar (2 September 2022) took place on location during the regular NETWORKS seminar series at Leiden University. Presentations were given by Eelke Heemskerk (UvA) and Bernd Heidergott (Tinbergen) about a network view on aging and mortality.
The seminar series will continue in 2023, on location at the Tinbergen Institute.

OUTREACH

MASTERCLASS NETWORKS GOES TO SCHOOL

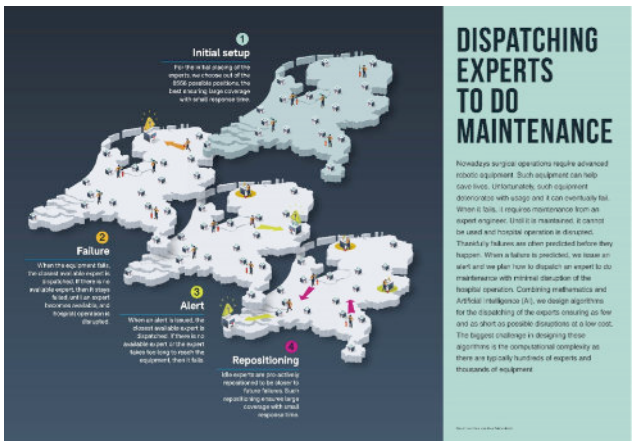
In March and April 2022, the yearly masterclass “NETWORKS goes to school” was organized. This masterclass on the mathematics of networks is held in English and hence suitable for international schools as well. The masterclass contained two lectures, which were held online via Zoom, and one full day on the campus of the University of Amsterdam. The lectures were given by Giulia Bernardini (CWI) and Roel Lambers (TU/e). The number of participants was very low compared to other years. Only 5 students participated in the events, although 25 were registered.
All the material presented during the masterclass was gathered in a booklet. The online lectures were recorded and are available for educational purposes. One teacher asked for and used the online recordings and the material of the masterclass as part of the Mathematics D course at their school. This was evaluated positively by both the teacher and the students.

PUBLIC EVENT ON FAKE NEWS

In 2022 Leiden was the very first European City of Science, involving a year-long program aimed at connecting science and society. In this framework, NETWORKS organized a public event on Fake News at the University of Leiden, entitled “From Fact to Fake”. In three lectures, fake news was discussed from different points of view: the importance of fact checking, the dangers of echo chambers, and the sociological effects of fake news. About 125 participants attended the meeting.

IMAGINARY

Throughout the school year 2022-2023, the exhibition IMAGINARY could be visited and experienced in various cities across the Netherlands. This travelling exhibition was organized by the Dutch Platform for Mathematics, in collaboration with Dutch universities, and supported by partner organizations. It included numerous top-quality posters, a series of 3D objects, puzzle setups, and several interactive apps that visitors could engage with via large touchscreens. There were also free guided tours for school classes and other interested parties at each location. NETWORKS presented four posters on networks and algorithms:



Poster created by Stella Kapodistria and Peter Verleijsdonk, in collaboration with the Network Pages. The design of the poster was made by WAT Ontwerp.

- The Travelling Salesman Problem, by Frans de Ruiter from the Dutch datascience company CQM in Eindhoven.
- Dispatching experts to do maintenance, by Stella Kapodistria (TU/e) and Peter Verleijsdonk (TU/e)
- Structure in social networks, by Clara Stegehuis (UT)
- From tweets to communication, by Anna Priante (EUR)

The exhibition opened its doors at Leiden University on 2 June 2022. In the fall, the exhibition was hosted by TU/e. In 2023, IMAGINARY will be hosted by the University of Amsterdam.

INTERNATIONALIZATION

NETWORKS continues its fruitful collaboration with the Indian Statistical Institute (ISI). Several joint projects with researchers in Bangalore and Kolkata are ongoing, complemented by visits back and forth. A joint workshop at the International Center for Theoretical Science in Bangalore is planned for January 2024.

The collaboration with Australian researchers in Melbourne and Sydney also continues to bear fruit via ongoing joint projects. In September 2022, NETWORKS organized the second fully online conference Data Driven Queueing Challenges (DDQC II), this time on management of service systems, in collaboration with the ARC Centre of Excellence for Mathematical & Statistical Frontiers (ACEMS). The objective of this workshop was to highlight and discuss contemporary approaches to the management of service systems, with a focus on data collection, methodological insights, and analysis of decision making.
The workshop was designed to appeal to researchers with backgrounds in statistics, stochastic modelling, data science, and

control to discuss challenges in stochastic operations research and operations management. Workshop sessions spanned international time zones to be accessible to multiple audiences. In 2021, when the world was in lockdown due to COVID, DDQC I was a great success with over 300 subscriptions and about 60-100 participants per session 200 people registered, but on average 20 people attended the various sessions. We are reconsidering if we will organize a third DDQC conference in 2023, since the participants indicated that they prefer to attend live meetings over the online conference

EUROPEAN COFUND GRANTS

In February 2020 NETWORKS received a COFUND grant of around € 1.5 million euro from the EU Horizon2020 program. With this grant, NETWORKS was able to hire 14 new PhD students in the period 2020-2025. In 2021 NETWORKS was granted another COFUND grant of € 1.0 million to appoint 14 postdoctoral researchers for 2 years. The aim of the COFUND program is to strengthen international research collaborations and to improve scientific mobility.

All PhD positions in the COFUND grant have been filled. In October 2022 the midterm evaluation of the program took place. The result was very positive, especially about the supervision and the training offered to the PhD students.

For the PD grant, two calls for recruitment were published, leading to 9 positions filled at the end of 2022. Another call to fill up the remaining open positions will be organized early 2023.

Via the two COFUND grants, new international contacts were forged, which brought top junior talent to The Netherlands. Several junior and senior members of NETWORKS took part in the organization of workshops and summer schools abroad, e.g. in Vacouver and Montreal, Canada, in the Summer of 2022, and at the Simons Institute in Berkeley, USA, in the Fall of 2022.

AWARDS AND GRANTS

AWARDS

Best paper award SPIRE 2022

Wiktor Zuba and Solon Pissis – 29th International Symposium on String Processing and Information Retrieval for the article "Subsequence Covers of Words".

2022 IEEE INFOCOM Test of Time Paper Award

Sem Borst for the article "Distributed Caching Algorithms for Content Distribution Networks" in Proc. of IEEE INFOCOM 2010. by Martijn.

EDUCATION

The main components of the NETWORKS educational program are the biannual Training Weeks, the workshop Analytic Storytelling and the internships.

In 2022, both Training Weeks could be organized on location again at the Schildkamp in Asperen. Fixed components of the Training Weeks are introductory talks by new PhD students and postdocs, two minicourses, open problem sessions, research presentations by the members of NETWORKS, and a social event. The first Training Week was held from 9 – 12 May. The minicourses were given by Mark de Berg (TU/e) on fundamental techniques in computational geometry, and by Daniel Valesin (University of Warwick) on the contact process, highlighting recent results on finite-volume phase transitions. The second Training Week took place from 24 – 28 October with minicourses by Guus Regts (UvA) on partition functions and by Johannes Schmidt-Hieber (UT) on statistical theory for neural networks.

In 2018, we started professionalizing the writing of content through 'Analytic Storytelling' workshops, which help participants to write articles and to bridge the gap between their usual academic writing and the more outreach style that is needed for the Network Pages. Since 2020 the training is compulsory for all NETWORKS PhD students and postdocs. The articles written during the training are published on the Network Pages. In 2022 three more workshops were organized, in 2023 three workshops will be organized, as well.

WORKSHOPS

WORKSHOP	PERIOD	LOCATION	INVOLVED FROM NETWORKS
Parameterized Algorithms and Computational Experiments	Spring 2022	online	Bart Jansen
Dutch Day of Combinatorics	12 May 2022	TU Eindhoven	Jo Ellis-Monaghan
23rd Conference on Integer Programming and Combinatorial Optimization (IPCO)	27-29 June 2022	TU Eindhoven	Laura Sanitá, Frits Spieksma, Daniel Dadush
Francesca Romana Nardi: A life in probability, building communities across Europe	18-22 July 2022	University of Florence, Italy	Luca Avena
Summerschool Random Graphs (RANDNET)	24-31 August 2022	Eurandom, Eindhoven	Remco van der Hofstad, Joost Jorritsma
DDQC 2022: Management of service systems	20-22 September 2022	Online	Michel Mandjes
Recent Trends in Spatial Stochastic Processes	3-7 October 2022	Eurandom, Eindhoven	Pim van der Hoorn
YEQT XV: Machine Learning for Stochastic Networks	2-4 November 2022	Eurandom, Eindhoven	Jaron Sanders
Recent Developments in Stochastic Duality	12-16 December 2022	Eurandom, Eindhoven	Frank den Hollander
The Lorentz Gas	19-23 December 2022	Lorentz Center, Leiden	Frank den Hollander, Luca Avena

ORGANIZATIONAL ASPECTS

ORGANIZATIONAL DEVELOPMENTS

In the reporting period, 3 PhD students and 7 postdocs were appointed within the NETWORKS program. With these appointments, all PhD positions, including the COFUND positions, have now been filled up. Ross Kang was appointed at the UvA, as a successor or Viresh Patel, who accepted a position at the University of London. Marianne de Bruin succeeded Patty Koorn, who retired in Spring 2022.

By the end of 2022, NETWORKS counted 73 members and 47 affiliated members (who are not paid by the grant yet are strongly connected to the NETWORKS program). See page 24 for a complete overview of the NETWORKS members.

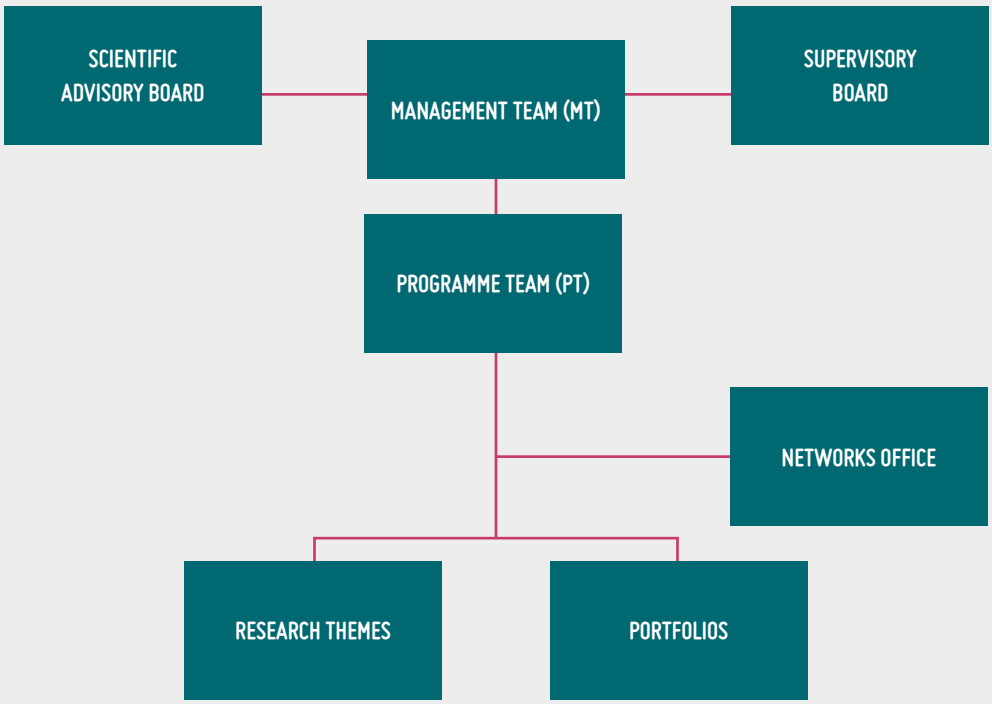
NETWORKS members and affiliated members convene two times a year during the so-called NETWORKS days. Both NETWORKS days could be held on location. The first NETWORKS day in June was organized at CWI. The second NETWORKS day took place in November in Eindhoven. During the NETWORKS days, new members introduce themselves and there are 3-4 research presentations mostly from researchers outside NETWORKS. Next to these presentations there is ample time to meet each other.

IN MEMORIAM

GERHARD WOEGINGER

On 1 April 2022, prolific computer scientist Gerhard Woeginger passed away. Born on 31 May 1964 in Graz, he studied at the Graz University of Technology, where he obtained his PhD under Franz Rendl in 1991. He became a professor at UT in 2001, and joined TU/e as a professor in 2004. In 2016 he moved to RWTH Aachen. Woeginger worked in almost every field within theoretical computer science: social choice, bibliometrics, algorithms, approximability, computational geometry, and computational complexity. He was involved in the organization of many conferences, created the P-versus-NP website, and was vital to the Christmas puzzle (Adventskalender). In his obituary, Frits Spieksma writes: "His talent to see connections between different problems was amazing. And his drive and enthusiasm to distinguish easy from hard, was absolutely infectious. Above all, he could listen – he was able to identify truth in one's unstructured words. And then he'd write the paper, faster than one thought was possible. The math and computer science department of TU/e, as well as the NETWORKS community, owe him a lot – we are very grateful for his time spent here. His friendliness combined with a deep mathematical curiosity has been a source of inspiration for all around him."

ORGANOGRAM



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prof. dr. Frank den Hollander (UL)
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dr. Marieke Kranenburg, project manager
Marianne de Bruin, workshop officer
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Tiny Dekker, webmaster
Nicos Starreveld, outreach

PORTFOLIOS

Workshops
Outreach
Internationalization
Education
Valorization
Network Pages

RESEARCH THEMES

Approximate and exact network methods
Spatial networks
Quantum networks
Dynamics of networks
Dynamics on networks
Transportation and traffic networks
Communication and energy networks

NETWORKS MEMBERS

NAME	FUNCTION PROFILE	AFFILIATION
Henk Alkema, MSc	PhD student	TU/e
Dr. Elene Anton Balerdi	Postdoc	TU/e
dr. Luca Avena	Asst. Professor	UL
prof.dr. Mark de Berg	Professor	TU/e
Bharti, MSc, MPhil	PhD student	UvA
Wessel Blomerus, MSc	PhD student	TU/e
Shreehari Bodas, MSc	PhD student	UvA
prof.dr.ir. Sem Borst	Professor	TU/e
prof.dr.ir. Onno Boxma	Professor	TU/e
dr. Peter Braunsteins	Postdoc	UvA
dr. Jop Briët	Asst. Professor	CWI
Ruben Brokkelkamp, MSc	PhD student	CWI
Marianne de Bruin	Support Staff	TU/e
prof.dr. Harry Buhrman	Professor	UvA, CWI
Federico Capannoli, MSc	PhD student	UL
Dr. Davi Castro Silva	Postdoc	CWI
Suman Chakraborty	Postdoc	TU/e
Dr. Benoît Corsini	Postdoc	TU/e
Tiny Dekker	Support Staff	UvA

NAME	FUNCTION PROFILE	AFFILIATION
Pierfrancesco Dionigi, MSc	PhD student	UL
dr. Jan-Pieter Dorsman	Asst. Professor	UvA
Tim Engels, MSc	PhD student	TU/e
Francisco Escudero, MSc	PhD student	CWI
Hans de Ferrante, MSc	PhD student	TU/e
Dr. Martin Frohn	Postdoc	TU/e
Diego Goldsztajn, MSc	PhD student	TU/e
Martijn Gösgens, MSc	PhD student	TU/e
Rowel Gündlach, MSc	PhD student	TU/e
prof.dr. Remco van der Hofstad	Professor	TU/e
prof.dr. Frank den Hollander	Professor	UL
Dr. Royi Jacobovic	Postdoc	UvA
Agnieszka Janicka, MSc	PhD student	TU/e
dr. Bart Jansen	Assoc. Professor	TU/e
Purva Joshi, MSc	PhD student	TU/e
Rens Kamphuis, MSc	PhD student	UvA
Dr. Ross Kang	Assoc. Professor	UvA
dr. Stella Kapodistria	Tenure Track	TU/e
Ellen Konijnenberg	Support Staff	TU/e

Asst. Professor = Assistent Professor
Assoc. Professo = Associate Professor

NETWORKS MEMBERS

NAME	FUNCTION PROFILE	AFFILIATION
Patty Koorn	Support Staff	TU/e
Twan Koperberg, MSc	PhD student	UL
Gianluca Kosmella, MSc	PhD student	TU/e
dr.ing. Marieke Kranenburg	Support Staff	UvA
Lucas van Kreveld, MSc	PhD student	UvA
Boris Lebedenko, MSc	PhD student	UvA
Nikki Levering, MSc	PhD student	UvA
Andrés López Martínez, MSc	PhD student	TU/e
Roshan Mahes, MSc	PhD student	UvA
Nandan Malhotra, MSc	PhD student	UL
prof.dr. Michel Mandjes	Professor	UvA
Benedikt Meylahn, MSc	PhD student	UvA
Marta Milewska, MSc	PhD student	CWI
Maurizio Moreschi, MSc	PhD student	UvA
Dr. Noela Müller	Asst. Professor	TU/e
Oliver Nagy, MSc	PhD student	UL
prof.dr. Sindo Núñez Queija	Professor	UvA
Manish Pandey, MSc	PhD student	TU/e
Tom Pijnappel, MsC	PhD student	TU/e

NAME	FUNCTION PROFILE	AFFILIATION
Dr. Matteo Quattropani	Postdoc	UL
Rounak Ray, MSc	PhD student	TU/e
Arpan Sadhukhan, MSc	PhD student	TU/e
prof.dr. Frits Spieksma	Professor	TU/e
dr. Patty Stabile	Assoc. Professor	TU/e
Nicos Starreveld, MSc	Support Staff	UvA
prof.dr. Leen Stougie	Professor	CWI
Michelle Sweering, MSc	PhD student	CWI
Leonidas Theocharous, MSc	PhD student	TU/e
Philip Verduyn Lunel, MSc	PhD student	CWI
Daoyi Wang, MSc	PhD student	UL
Sten Wessel, MSc	PhD student	TU/e
Mehmet Akif Yildiz, MSc	PhD student	UvA
Haodong Zhu, MSc	PhD student	TU/e
Dr. Wiktor Zuba	Postdoc	CWI

NETWORKS-COFUND PROJECTS / PHD PROJECTS

PHD STUDENT	TITLE	SUPERVISORS	AFFILIATION
Bharti	Stochastic Decision Making for Spatial Problems	Michel Mandjes, René Bekker	UvA
Wessel Blomerus	Structured Learning for Stochastic Optimization: Algorithm Design and Convergence	Stella Kapodistria, Sem Borst	TU/e
Shreehari Bodas	Estimation of model primitives based on partial information	Michel Mandjes, Liron Ravner	UvA
Federico Capannoli	Interacting particle systems on random graphs	Rajat Hazra, Frank den Hollander, Remco van der Hofstad	UL
Francisco Escudero	Quantum query complexity	Jop Briët, Harry Buhrman	CWI
Purva Joshi	Optimal Routing of Autonomous Vehicles	Marko Boon, Sem Borst	TU/e
Gianluca Kosmella	Modeling and Analysis of Optical Neural Networks across Photon Density Regimes	Patty Stabilé, Jaron Sanders	TU/e
Boris Lebedenko	Inverse based input estimation in stochastic networks	Michel Mandjes, Liron Ravner	UvA
Andrés López Martínez	The stability of online algorithms	Frits Spieksma, Mark de Berg	TU/e
Nandan Malhotra	Spectra of Random graphs	Rajat Hazra, Luca Avena, Frank den Hollander	UL
Ben Meylahn	The dynamics of trust networks	Arnoud den Boer	UvA
Marta Milewska	Understanding superspreading phenomena of epidemics on complex networks	Bert Zwart, Remco van der Hofstad	CWI
Rounak Ray	Percolation and Random Walks on Preferential Attachment Models	Remco van der Hofstad, Frank den Hollander	TU/e
Mehmet Akif Yildiz	Extremal, algorithmic, and enumerative problems in graph theory	Viresh Patel, Jo Ellis-Monaghan	UvA
Haodong Zhu	Statistical mechanics of and on random graphs	Remco van der Hofstad, Noëla Müller	TU/e

The projects listed above has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 945045.

NETWORKS-COFUND PROJECTS / POSTDOC PROJECTS

POSTDOCTORAL FELLOW	TITLE	SUPERVISORS	AFFILIATION
Benoît Corsini	Developments on the Configuration Model	Remco van der Hofstad, Noëla Müller	TU/e
Royi Jacobovic	Some new results about an old model: The M/G/1 queue	Michel Mandjes, Onno Boxma	UvA
Wiktor Zuba	Algorithms on strings and labelled graphs	Leen Stougie, Solon Pissis	CWI
Martin Frohn	A new information theory perspective on network design in phylogenetics and beyond	Frits Spieksma, Leen Stougie	TU/e
Elene Anton Balerdi	Stability and performance of multi-class queueing systems with unknown service rates: A combined scheduling-learning approach	Sem Borst	TU/e
Matteo Quattropani	Voter model and coalescent random walks on random graphs	Frank den Hollander, Luca Avena	UL

The projects listed above has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034253.

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