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 2020 & 2021

The years 2020 and 2021 will be remembered as the year of the COVID-19 pandemic. Needless to say, this pandemic has had an enormous impact on our private and professional lives. In this seventh year of NETWORKS' funding period we have been creative in finding ways to make sure that everything could go on as much as possible.

Like almost everyone, the pandemic took us by surprise. Concretely, for a long time we were not sure whether our on-site NETWORKS-wide seminar of March 11 could proceed. At the very last moment, we decided to cancel it. In the weeks to follow, the Netherlands, and as a matter of fact essentially the whole world, came to a full standstill.

The virus, and the measures that were taken to contain it, have seriously affected our activities. Without the possibility of meeting face-to-face, all collaborations became much harder. We have had to resort to online video services such as Zoom, Teams, and Skype to interact. This turned out to be significantly less efficient than our usual in-person meetings: a mathematician feels uncomfortable without a blackboard (or whiteboard) to communicate ideas. In addition, all of us were asked to very quickly migrate to online teaching, which was a time-consuming and somewhat stressful transition.

As a result, 2020 and 2021 have been highly challenging years. Within the NETWORKS management, we have been consistently aware of the dangers that we are facing, most notably a loss of morale or even mental health issues. In the four teams involved in NETWORKS we have been very alert to detect potential problems as quickly as possible.

This does not mean that there was only bad news. A highlight was the news that we were awarded a COFUND grant for PhD students in March 2020 and another COFUND grant for attracting additional postdocs in March 2021. With these European grants, of about 1.75 M€ and 1.0 M€ respectively, we could double our remaining PhD and postdoc positions. It allows us to start new exciting 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, with a significantly better connection with various adjacent disciplines.

Within the program offered to the new COFUND students, there will be a strong emphasis on educating these young people. This, in the first place, amounts to offering them a background in topics that typically go considerably beyond the topic their own project, as has always been our intention in NETWORKS. Also, an integral part of the PhD project is an industrial traineeship, in which mathematical concepts are applied in a more operational context. The pandemic has emphasized the need of training good modelers.

We again had an impressive scientific output, resulting in many impactful publications in leading journals on probability, combinator-

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ics, operations research, and algorithmics. Although the program is well under way, new interactions keep arising: in the context of the new PhD projects, interesting new interfaces have been identified. In addition, we increasingly team up with colleagues working on networks in the context of the social sciences and economics. A very inspiring three-day workshop was held in January (still on-site!), followed by two shorter online events, which already led to concrete joint research projects.

A wonderful new initiative was the workshop on Data-driven Queueing Systems, co-organized with our fellow research network ACEMS from Australia and the Alan Turing institute in the United Kingdom. The program targeted at audiences in three continents (Australia, Europe and the Americas), with recorded presentations for those who missed one because they were asleep… We received very positive feedback — there was a clear need for a workshop revolving around this highly timely theme. We managed to attract top-notch speakers who gave fantastic talks on state-of-the-art methodologies. Due the success of this first edition, we immediately decided to organize a second edition in 2022.

We are happy that the pandemic seems to be reaching its end. Actually, late 2021 quite a few offline activities were organized, and hopefully this line continues in 2022!

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 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

- In workflow scheduling for parallel computing, applications are modeled as directed acyclic graphs (DAGs). The DAG model assumes, in most cases, a fixed DAG structure capturing only straight-line code. Only recently, more general models have been proposed. In particular, the conditional DAG model allows the presence of control structures such as conditional (if-then-else) constructs. Leen Stougie (CWI) and co-workers presented a thorough analysis on the worst-case makespan (latest completion time) of a conditional DAG task under list scheduling. They showed several hardness results concerning the complexity of the optimization problem on multiple processors, even if the conditional DAG has a well-nested structure. For general conditional DAG tasks, the problem is intractable even on a single processor. They also showed that certain practically relevant special cases of the problem can be solved efficiently.

- Graph coloring is a long-studied notion in graph theory. Vizing's classical theorem on edge coloring states that one can partition the edges of any graph into at most D+1 matchings where D is the maximum degree of the graph. Edge colorings of graphs are closely related to problems in scheduling. Extending the notion of such edge colorings, one can ask to partition the edge set so that the parts have some given property rather than being matchings. NETWORKS researchers consider edge colorings of directed graphs in which each color class is a directed path. The minimum number of colors required in such a coloring is called the path number of the directed graph and has a very natural lower bound in terms of the degree sequence of the directed graph. Those digraphs for which the lower bound is attained are called consistent. In 1976, Alspach, Mason, and Pullman conjectured that every tournament with an even number of vertices is consistent. (A tournament is an orientation of the complete graph.) All cases of this conjecture remained open. Viresh Patel (UvA), together with Allan Lo (University of Birmingham), Jozef Skokan (London School of Economics), and John Talbot (University College London) proved many of them.

- Many fundamental NP-hard problems on graphs can be stated as vertex-deletion problems: delete a minimum number of vertices from a given graph such that the resulting graph has some desired property. In the Odd Cycle Transversal problem, for instance, the desired property is that the resulting graph is bipartite, and in the Planarization problem the desired prop-

erty is that the graph that can be drawn in the plane without edge crossings. Research into the parameterized complexity of these problems over the last two decades has led to FPT algorithms that find an optimal solution in polynomial time if the solution size k (that is, the minimum number of vertices to be removed) is small. Bart Jansen (TU/e), Jari de Kroon (TU/e) and Michal Wlodarczyk (TU/e) develop algorithms that run in polynomial time when the so-called elimination distance D is small. The elimination distance is defined as the minimum number of rounds to obtain the desired property, where in each round one can delete a vertex from every connected component. Since in practice D is often much smaller than k, this significantly extends the range of inputs for which these problems are tractable.

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

- Together with Michel Mandjes (UvA) and Paulo Serra (VU), NETWORKS PhD student Rens Kamphuis (UvA) devised algorithms for estimating travel time distributions in road traffic networks. These efficiently exploit the underlying spatial structure. Relying on a Bayesian approach, an estimator is constructed for the joint per-edge travel time distribution; in addition, performance guarantees are provided. The estimation procedure can be used to support decisions regarding optimal routing, also in case the objective function is, rather than the expected travel time, e.g. a quantile of the travel time.

- The Parabolic Anderson Model (PAM) is a classical model in mathematical-physics which corresponds to the Cauchy problem for the spatially discrete heat equation with a random potential defined on a graph. The model can be interpreted microscopically as a system of branching random walkers evolving on the underlying graph, and its solutions describe the evolution of the density of these random walkers in the set of vertices of the graph. Localization and other properties of these solutions have been widely investigated in the literature in several regimes though either on d-dimensional integer lattices or on the complete graph. Luca Avena (UL), Onur Gün (Weierstrass Institute), and Marion Hesse (Weierstrass Institute) instead looked at the PAM on a hypercube, one of the reasons being that in such a setup it can be interpreted as a mutation-selection model of population genetics on a random fitness landscape. They studied localization of the corresponding solutions and show a related phase transition for a class of potentials which includes the random energy model

studied in the physics literature as one of the main examples of a random fitness landscape.

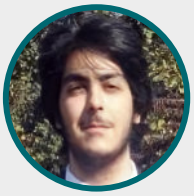
- In the Inventory Routing Problem (IRP), inventory management and route optimization are combined. Routing aspects make the general problem immediately NP-hard. Leen Stougie (CWI) and collaborators investigated how other aspects than routing influence the IRP complexity by studying IRPs on metric spaces on which routing is easy, like the half-line. Their main result was a polynomial time dynamic programming algorithm for the variant on the half-line with uniform service times and a planning horizon of two days. Second, they showed that for nearly any problem with non-fixed planning horizon establishing the complexity is related to a long-standing open research question. Third, NP-hardness was shown for problem variants with non-uniform servicing times. Finally, they proved NP-hardness of a Euclidean variant with uniform service times and an easily computable routing cost approximation.

- In spatial voting theory, the preferences of voters are modelled as points in a multi-dimensional policy space, where each dimension represents an issue that is at

NEW PERSONNEL

B. Bharti, MSc, MPhil
PhD, UvA

Wessel Blomerus
PhD, TU/e



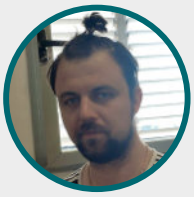
Federico Capannoli, MSc
PhD, UL

Tim Engels, MSc
PhD, TU/e

Francisco Escudero
PhD, CWI

Purva Joshi
PhD, TU/e

Gianluca Kosmella, MSc
PhD, TU/e



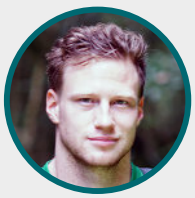
Boris Lebedenko, MSc
PhD, UvA

Nelly Litvak
Professor, TU/e

Andrés López Martínez
PhD, TU/e

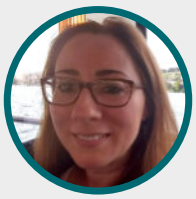
Roshan Mahes, MSc
PhD, UvA

Nandan Malhotra, MSc
PhD, UL



Benedikt Meylahn
PhD, UvA

Dr. Noela Müller
Tenure Track, TU/e



Dr. Patty Stabile
Asst. professor, TU/e

Mehmet Akif Yildiz, MSc
PhD, UvA

Haodong Zhu, MSc
PhD, TU/e

stake in an election. For instance, each dimension can represent how much funds should be allocated to address the corresponding issue. A candidate in the election can also be represented as a point in the policy space, according to the candidate's opinion on the issues. In the spatial voting model, each voter will then vote for the candidate whose opinion is nearest to their preference. Now suppose the election has two candidates, A and B, where candidate A has to publicly announce her opinion – that is, pick a point in the policy space – before candidate B. In general, no matter which point is picked by candidate A, candidate B can always pick a point in the policy space so that she will win the election. Mark de Berg (TU/e), with Boris Aronov (NYU), Joachim Gudmundsson and Michael Horton (both University of Sidney) studied what happens when candidate A has some advantage over candidate B, for example because she is more likeable or can spend more campaign money. This can be modeled by scaling the perceived distance of each voter's preference to the point picked by A, with some factor $\beta<1$. De Berg and co-workers investigate how small β should be such that candidate A can always pick a point that wins the election, no matter which point candidate B will pick.

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

- Work of Jop Briët (CWI), Tom Bannink (CWI), Farrokh Labib (CWI) and Hans Maassen (RU and UvA), entitled "Quasirandom quantum channels", won the Outstanding Paper Award at the conference TQC 2020 and was published in the Diamond Open Access journal *Quantum*. This work generalizes old and recent results about 'quasirandom' graphs to quantum channels, which represents the most general quantum operation admissible by quantum mechanics, using Grothendieck-type inequalities from functional analysis and representation theory of CAR algebras. Furthermore, a recent result on quasirandom Cayley graphs of Conlon and Zhao was shown to be optimal.

- Two works of Briët and Labib with Ben Green (University of Oxford) showed that multiple correlation sequences have unexpectedly high entropy numbers. Such sequences appear naturally at the intersection of ergodic theory and probabilistic combinatorics, where they count the number of arithmetic progressions with a given common difference in subsets of the integers or other abelian groups. The results imply an obstacle to a proposed route for proving vast generalizations of Szemerédi's theorem, conjectured by ergodic theorists Frantzikinakis, Lesigne and Wierdl. These generalizations are closely related to connectivity properties of certain hypergraphs.

DEVELOPMENTS OUTSIDE OF NETWORKS

- The year 2020 marked the 5-year lustrum for QuSoft, which was celebrated with a month of activities. After five years, Jos Baeten (director CWI) and Peter van Tienderen (dean FNWI) signed the agreement that continues this collaboration. “I am very glad that nine years ago, when I started as director of CWI, Harry Buhrman convinced me to invest in his idea of a new research institute for quantum software”, Baeten said.

- QuSoft, CWI, and UvA jointly established a new innovation hub for developing quantum software and applications. The Quantum.Amsterdam hub aims to connect the ambitions of leading knowledge institutes and industry partners. Briët joined its management team.

- The Dutch government decided to invest 23.5 million euros in the coming five years in quantum technology, meant as a financial advance for the execution of the National Agenda Quantum Technology[1].

- To accelerate the leading role of the Netherlands in quantum technology, a new institution was established: Quantum Delta Nederland (QDNL) Foundation. By expanding the current ecosystem of companies, knowledge institutes, and governmental institutions, QDNL will continue to build a strong ‘Quantum Delta’. QDNL was founded by a broad collaboration of knowledge institutes, companies, and social organizations, including QuSoft (UvA and CWI), TUD, UL, TU/e, UT, TNO, TechLeap, Braventure, NanoLabNL, MinacNed, and NanoNextNL. In total, more than 70 companies and organizations are involved.

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

- Luva Avena (UL), Hakan Guldas (UL), Remco van der Hofstad (TU/e), Frank den Hollander (UL), and Oliver Nagy (UL) considered non-backtracking random walks on random graphs generated according to the configuration model. The quantity of interest is the scaling of the mixing time of the random walk as the number of vertices of the random graph tends to infinity. Subject to mild general conditions, two mixing times are linked: one for a static version of the random graph, the other for a class of dynamic versions of the random graph in which the edges are randomly rewired but the degrees are preserved. This link is used to compute the scaling of the mixing time for three specific classes of random rewirings.

- Peter Braunsteins (UvA), Frank den Hollander (UL), and Michel Mandjes (UvA) studied dynamic Erdös-Rényi random graphs. In these models 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

[1] *www.rijksoverheid.nl/actueel/nieuws/2020/02/17/235-miljoen-euro-voor-start-uitvoering-nationale-quantumagenda*

developed. 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. A number of new phenomena were observed that are not present in the static case.

THEME 5: DYNAMICS ON NETWORKS

While random processes in static random structures are relatively well understood, their analysis in the dynamic setting is still in its infancy. In this theme, stochastic processes on randomly evolving networks are studied.

HIGHLIGHTS

- Suppose that periodic observations of a network population are conducted. Then what can be said about the input processes of the underlying stochastic network? With various coauthors, Michel Mandjes (UvA) has looked into this question. With Liron Ravner (UvA), he derived asymptotically normal estimators in case the input process is Lévy, and developed procedures to resolve the corresponding hypothesis testing problem. This led to papers in *Bernoulli* and in *Stochastic Processes and their Applications*. With Birgit Sollie (VU), he considered general network structures in discrete time, with focus on efficient saddle-point-based computational procedures to evaluate the likelihood. A paper with Sophie Hautphenne (University of Melbourne) and Mathisca de Gunst (VU) appeared in *Stochastic Models*. With Martin Zubeldia (TU/e & UvA), he focussed on Gaussian networks. With the help of Schilder's theorem, bounds on decay rates were established, culminating in data-driven efficient load-balancing algorithms.

- PageRank is a well-known algorithm for centrality in networks. It was originally proposed by Google for ranking pages in the World Wide Web. One of the intriguing empirical properties of PageRank is the so-called 'power-law hypothesis': in a scale-free network, the PageRank scores follow a power law with the same exponent as the (in-)degrees. To date, this hypothesis has been confirmed empirically and in several specific random graphs models. Alessandro Garavaglia (TU/e), Remco van der Hofstad (TU/e), and Nelly Litvak (UT) did not focus on a single random graph model. Instead, using local weak convergence, they investigated the existence of an asymptotic PageRank distribution when the graph size goes to infinity. The limiting distribution of PageRank was computed directly as a function of the limiting object. The results were applied to the directed configuration model and to continuous-time branching processes trees, as well as to preferential attachment models. This work has been used by Sayan Banerjee and Mariana Olvera-Cravioto (University of North Carolina) to show that the power-law hypothesis is false for preferential attachment models.

- Den Hollander and Daoyi Wang (UL) considered the large-time asymptotics of the total mass of the solution to the parabolic Anderson model on a supercritical Galton-Watson random tree with a random potential whose marginal distribution is double-exponential. Under the assumption that the degree distribution has a sufficiently thin tail, two terms in the asymptotic expansion are identified under the quenched law, i.e., conditional on the realisation of the random tree and the random potential. The second term contains a variational formula indicating that the solution con-

centrates on a subtree with minimal degree according to a computable profile. Future work will concentrate on what happens under the annealed laws, i.e., when the average is taken over the random tree and/or the random potential.

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 (UvA), Marko Boon (TU/e), Michel Mandjes (UvA) and Sindo Núñez Queija (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 effect on the driveable speeds of both random traffic events and more deterministic traffic patterns. It was shown that, from the perspective of a single driver, an optimal route can be determined by dynamic programming. To overcome the complexity issues, global independence and computable heuristics were used to design a real-time routing algorithm, which was tested in the Dutch road network, using data of the NDW (Nationaal Dataportaal Wegverkeer). This research has resulted in two papers. The first paper, which focusses mainly on the theoretical concepts and introduces the novel routing algorithms has been published in Transportation Research Part B. The second paper, which is almost ready for submission to a transportation journal, illustrates how to operationalize the model using the NDW data.

- In earlier work, Jaap Storm (VU) and Mandjes (UvA) have shown for a stochastic traffic flow model that traffic densities, broken down into different vehicle types, propagate through a road traffic network according to (approximately) a Gaussian process. In the past year, in a follow-up project, they have shown by means of data analysis with historical traffic flow data, that such a Gaussian approximation is reasonable to use in practice. They also used simulation to show that relaxing the model assumptions, which are relatively stylized for technical reasons, does not significantly affect the vehicle density distribution.

- In another project, Wouter Kager (VU), Mandjes (UvA), Sem Borst (TU/e), and Storm (VU) studied stochastic ring networks. Such networks often occur in the context of communication systems but are also found in traffic networks such as roundabouts. By coupling the respective class of models to multiclass queueing networks, they were able to determine global stability criteria for these types of networks.

- Together with their PhD student Han Zhou (UvA and TNO) and with Maaike Snelder (TNO), Jan-Pieter Dorsman (UvA) and Mandjes (UvA) developed methods for assessing the impact of ‘mobility-as-a-service’. If this concept would be adopted, it would entail that travelers move away from conventional personally-owned modes of transportation, towards mobility

that is provided as a service, typically involving both public and private transportation providers. At the methodological level, the performance assessment requires new techniques to facilitate large agent-based simulations. The objective is to set up methodologies that enable efficient evaluation of policies.

- PhD student Rik Timmerman together with Marko Boon, Guido Janssen and Johan van Leeuwaarden (all TU/e), developed heavy-traffic limits for the fixed-cycle traffic-light queue, and leveraged this to obtain sharp performance approximations. Inserting those heavy-traffic approximations in an optimization problem was shown to lead to close-to-optimal green settings. Rik Timmerman successfully defended his PhD thesis in January 2022. Other models analyzed in this thesis include a fixed-cycle traffic light queue with various blocking mechanisms and platoon forming algorithms for future intersections with autonomous vehicles.

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.

HIGHLIGHT

MARGRIET OOMEN OBTAINS PHD CUM LAUDE

Margriet Oomen successfully defended her PhD thesis "Spatial Populations with Seed-Bank" at Leiden University on November 18, 2021. Frank den Hollander (Leiden University) and Andreas Greven (Erlangen-Nurnberg University) acted as promotors. The degree was awarded "cum laude".

In her thesis, Oomen studies the evolution of multi-colony genetic populations subject to resampling (change of type) and migration (change of colony) in the presence of a seed-bank where individuals can temporarily retreat (dormancy). She showed that there is a delicate interplay between these three evolutionary forces. She unraveled how the seed-bank enhances genetic diversity, clarified the role of heavy tails in the wake-up time distribution, and in doing so opened up new directions for research in population genetics.

HIGHLIGHTS

- Bart Post (TU/e) successfully defended his PhD thesis entitled "Load-Driven Self-Organization of Radio-over-Fiber Enabled Dense Cellular Networks" on February 26, 2020 under the supervision of Ton Koonen (TU/e) and Sem Borst (TU/e) and in close collaboration with Hans van den Berg (TNO). He developed resource allocation algorithm for dense cellular networks, specifically accounting for cutting-edge Radio-Over-Fiber technology, which are self-organizing in nature and do not need manual interventions. Post thoroughly analyzed the behavior of the algorithms using an extensive self-built simulation framework, and demonstrated that they significantly outperform the ones currently applied in operations.

- Another important research topic in this theme concerns the study of single-server queues with heavy-tailed service times. It is well known that the tail of the response

time distribution depends greatly on the service policy, but how exactly remains intriguing. Where prior research was focused on individual service policies, Lucas van Kreveld (UvA), together with researchers Ziv Scully (Carnegie Mellon University) and Adam Wierman (Caltech) as well as supervisors Onno Boxma (TU/e) and Jan-Pieter Dorsman (UvA), focused on a broad class of policies. In an ACM SIGMETRICS 2020 paper they provided a class of service policies where the corresponding response time distribution is so-called 'tail-optimal'. Moreover, they showed that this class contains certain important policies for which the property was still unknown to hold, including the Shortest Expected Remaining Processing Time First and Gittins policies.

- An important thread of research revolves around queueing systems that possess a stationary distribution with a per-job product form, a prominent example being redundancy scheduling policies which provide a popular mechanism for improving delay performance in parallel-server systems. A paper by Jan-Pieter Dorsman (UvA), together with Urtzi Ayesta (CNRS/IRIT, France), Tejas Bodas (IIT Dharwad, India) and Maaike Verloop (CNRS/IRIT, France), appeared in 2020 in the journal *Operations Research*, and provided a broad framework which captures many of these 'product-form' queueing systems. This framework subsumes multiple families of systems that were already known to have a product form, and provides a unified performance analysis. As a by-product, several performance measures of parallel-server systems with common redundancy scheduling policies were computed that were previously unknown.

- More recently, in the same field of research, Jan-Pieter Dorsman (UvA) and Céline Comte (TU/e) developed the so-called pass-and-swap queue. This is an extension of an existing product-form queueing model, known as the order-independent queue, supplemented with a sophisticated customer routing policy. Despite this queueing model not being covered by any existing 'product-form framework', Comte and Dorsman established that this queue does have a product-form stationary distribution. While this is in itself an important discovery, they also showed that closed networks of pass-and-swap queues retain this product-form nature, and that these networks can be used to describe the dynamics of existing and new redundancy scheduling policies in many-server systems.

- Diego Goldsztajn, together with Johan van Leeuwaarden and Sem Borst (all TU/e), studied load balancing algorithms for systems of parallel server pools. Their work has applications in the context of data centers and cloud computing platforms supporting video streaming or online gaming, where the level of congestion has a significant impact on the experience of users. In a joint paper with Debankur Mukherjee (Georgia Tech) and Philip Whiting (Macquarie University), they proved through fluid and diffusion limits that a threshold-based dispatching rule achieves the desired load balance asymptotically, provided that the threshold is optimally chosen in terms of the offered load. They also demonstrated that a token-based learning scheme can dynamically track the offered load and maintain the threshold at the optimal value. This establishes that a self-learning threshold policy, which combines the dispatching rule and the learning scheme, can be efficiently deployed in large-scale systems where the offered load is uncertain and time-varying.

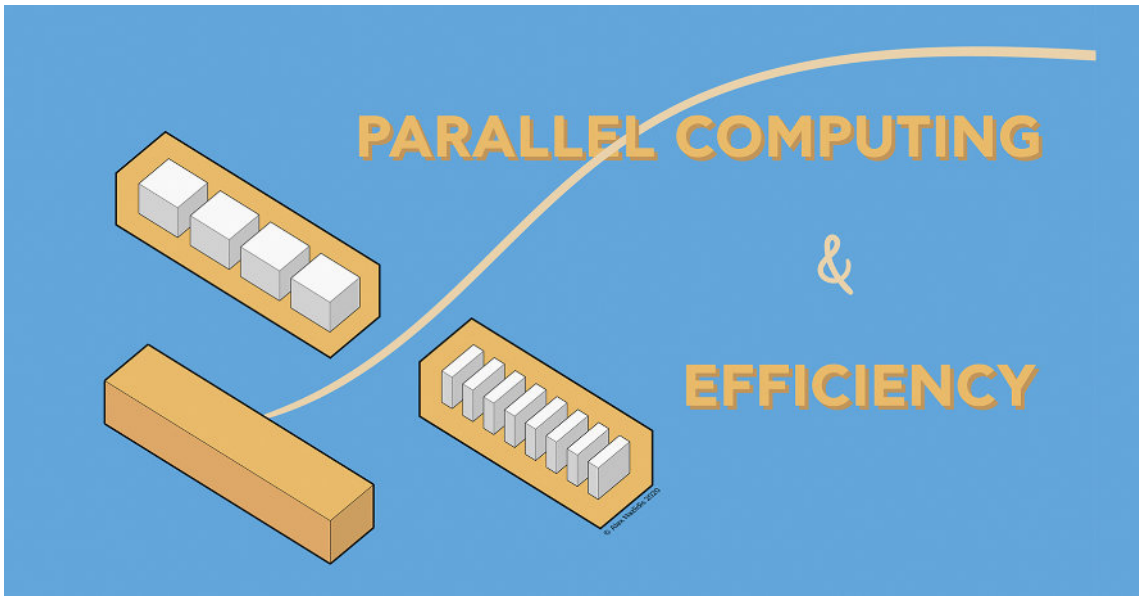
PORTFOLIOS

NETWORK PAGES

The Network Pages[2] 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. Martijn Gösgens, who is a PhD student at the TU/e, and Thom Carstemans, who works at the TU/e as animation developer, worked on developing various animations for the NetworkPages. In 2020 three animations were developed, in 2021 two more. Gösgens and Carstemans also developed an online networks game for the yearly study day of the association of secondary education teachers. The goal of the animation was to present in an interactive way some aspects of networks. The participants of the study day were positive about it, and in 2021 the authors of the game developed it into an independent online game that teachers can use in the class with their students. Late 2021 Carstemans left the TU/e and also the NetworkPages team.

In 2020 we continued with expanding our network. An article of Remco van der Hofstad (TU/e) was cross-published on the Network Pages and on the science communication platform Wetenschap.nu. Two articles of Frits Spieksma (TU/e) were also cross-published on both platforms. An initiative of Pierfrancesco Dionigi (UL) has led to a collaboration with the website of the European Mathematical Society where we plan to cross-publish about one article per month. In 2021 a LinkedIN group and a Twitter account were created, these channels are used to promote new material. New articles are also promoted via the outreach teams of the institutes where the author of the article works. In 2021 we also worked together with Alex Nazlidis, a professional science illustrator, who developed two illustrations for the Network Pages.



One of the illustrations Alex Nazlidis made for the Network Pages.

[2] *https://www.networkpages.nl*

In 2018, we started professionalizing the writing of content through 'Analytic Story Telling' 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. The previous workshops have received very good evaluations, both from the participants and from the site's editor in chief, Nicos Starreveld, who coordinates with the trainer in charge of the workshop. In 2020 we organized one workshop; the second one was postponed to the beginning of 2021. In 2021 two workshops were organized, both with great success. From now on the workshops are part of the regular activities for NETWORKS members.

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 are successful interactions with TNO. After the successful completion of the PhD project of Bart Post (TU/e) in early 2020, the collaboration with Hans van den Berg has continued in the PhD project of Tom Pijnappel (TU/e) which is co-funded by TNO and also involves Remco Litjens of TNO.

IN MEMORIAM

FRANCESCA NARDI

On October 21 2021, we received the sad news that Francesca Nardi passed away after a long illness. Nardi has always had a close relationship with the Netherlands, and with Eindhoven in particular.

She was appointed as one of the first tenure trackers in the WISE program in 2006, and was promoted to associate professor in 2015. Nardi returned to Florence in Italy in 2016, where she successfully built up a young and devoted group in probability. She continued to be affiliated with TU/e and with the Gravitation project NETWORKS, and came to the Netherlands often and gladly. Nardi has worked extensively with the probability group in Leiden, especially in the field of metastability, in which she was recognized as a world leader.

Nardi was a very enthusiastic researcher and lecturer, and always had a keen eye for the people involved. She was very beloved. The probability community in the Netherlands loses a prominent probabilist, and a wonderful and very warm person.

The goal of this PhD project is to explore the potential benefits of combining data-driven and model-based approaches (e.g. "expert knowledge aided deep learning"), provide benchmarks of achievable gains in various scenarios, and develop concrete algorithms for specific use-cases in 5G networks. In 2020 the work specifically focused on the optimal deployment of drone base stations to safeguard coverage and provide capacity relief when cellular networks experience stress conditions due to special events with massive crowds or network outages for example.

Danny Chan does his PhD project at UvA and Transtrend, focusing on a topic concerning opinion dynamics. He succeeded in devising a relatively basic model that is broad enough to reproduce a wide spectrum of commonly observed phenomena.

The research has been done in close collaboration with Andreas Flache, of the Faculty of Social and Behavioral Sciences of the University of Groningen.

In a separate valorization effort, Youri Raaijmakers (TU/e) worked for four months in the Next Generation Wireless department at Nokia Bell Labs in Stuttgart as part of his NETWORKS internship. Together with Silvio Mandelli and Mark Doll, he pursued the design of admission control algorithms for 5G wireless networks, and specifically focused on threshold-based and reinforcement learning policies in the presence of challenging features like time-varying channel rates and user mobility.

MATCHMAKERS INITIATIVE

From 20 to 22 January 2020, NETWORKS organized the Networks Match Making Event, jointly with VU and the Gravitation Program SCOOP. The aim was 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. Over 45 participants from the academic partners and from research-intensive companies like CBS and Rabobank came to Kaap Doorn to exchange ideas about available theories, techniques and methods, and to identify common challenges.

The event started with 12 pitches by researchers from social and economic sciences. Out of these pitches, 8 topics were identified that were discussed in round table sessions. The main organizers Frank den Hollander (UL) and Ines Lindner (VU and Tinbergen Institute) look back on the event with great satisfaction. “Our interdisciplinary speed dating was very intense and eye-opening. I left with a creativity boost. I am looking forward to joint projects and feedback on how our research makes sense in areas outside our comfort zones.”

As a follow up, a seminar series “Networks Matchmakers” has been set up. Until now three seminars have been taken place online:

- 20 October 2020 with presentations by Danny Chan (Transtrend & UvA) & Michel Mandjes (UvA) about the dynamics of opinion networks, and Ines Lindner (Tinbergen & VU) and Valentin Flietner (Tinbergen & EUR) about networks models of frailty.
- 4 February 2021 with presentations by Vincent Buskens (Utrecht University) about interrelated dynamics of social networks and infectious disease spread, and Frank P. Pijpers (CBS & UvA) about network reconstruction and privacy preservation for large networks.
- 1 October 2021 with a presentation by Anna Priante (EUR) entitled “’Mo’ Together or Alone? Investigating the Role of Fundraisers’ Networks in Online Peer-to-Peer Fundraising” and a presentation by Frank Takes (UL) about population-scale social network analysis.

These seminars attracted about 30-50 participants. To reach a larger public than only the NETWORKS community, a separate website and newsletter have been set up[3].

In addition we organised a multidisciplinary workshop on transport and logistics: the three days event “Road Traffic Flow: Analysis, Optimization and Control” was organized by Sindo Nunez-Queija (UvA & CWI), Marko Boon and Rik Timmerman, (TU/e) and Jan-Kees van Ommeren (University of Twente) in a joint Dynafloat—NETWORKS collaboration. It took place in a hybrid set-

[3] *https://www.networksmatchmaking.nl*

WORKSHOPS

WORKSHOP	PERIOD	LOCATION	INVOLVED FROM NETWORKS
Parameterized Algorithms and Computational Experiments Challenge 2020	Spring 2020	Online	Bart Jansen
KNAW corona webinar: Mathematics and COVID-19	19 April 2021	Online	Frank den Hollander, Michel Mandjes
Fixed-Parameter Computational Geometry III	25-28 May 2021	Lorentz Center	Mark de Berg, Hans Bodlaender
Parameterized Algorithms and Computational Experiments Challenge 2021	Spring 2021	Online	Bart Jansen
YEQT XIV: "Load balancing and scheduling for distributed service systems"	7-9 June 2021	Online	Céline Comte, Youri Raaijmakers, Martín Zubeldía
DDQC 2021: Data-Driven Queueing Challenges	21-23 September 2021	Online	Michel Mandjes

ting (on-campus and online), was very successful with renowned speakers from the areas of both transportation research and stochastic networks.

OUTREACH

In 2020, a "Wisschrift" on graphs has been published. "Wisschriften" are workbooks on a mathematical or related subject for primary schools. Pupils can work independently with the maths at school, but also at home and learn everything about the subject in question. Together with the Stichting Vierkant voor Wiskunde, NETWORKS developed this Wisschrift on graphs. Topics in the Wisschrift are "How do you transport circus animals without them eating each other?", "How does a navigation system work?" and "How do you move all Scrooge McDuck's money?"

The Masterclass "Networks goes to school 2020", aimed at secondary schools, had to be cancelled due to the pandemic. The masterclass was planned for March 2020, but was postponed to March 2021. Presentations were given by Youri Raaijmakers (TU/e) about preventing queues in supermarkets growing large, Rens Kamphuis (UvA) about finding the optimal route in a road traffic network and Janusz Meylahn (UvA) about how synchronisation works.

INTERNATIONALIZATION

The existing collaborations with the Indian Statistical Institute (ISI), SAMBA (hosted by the University of Bath) and ACEMS (Australia) have been continued in 2020.

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 is able to hire 14 new PhD students in the period 2020-2025, effectively doubling the number of PhD students currently in the program. The aim of the COFUND program is to strengthen international research collaborations and to improve scientific mobility.

The consortium's grant application made an exceptional impression on the evaluation committee. They praised the multidisciplinary nature of the consortium, with collaboration between mathematicians and computer scientists as well as between academic, social, and industrial partners, along with an active outreach program for schools.
In 2020 a lot of effort has been put in the recruitment and selection process for the COFUND positions. The search process for these 14 PhD students was a bit different from previous recruitment rounds. In the first place, it was challenging due to the uncertainties related to the pandemic. Secondly, one of the requirements that the EU imposed was that the candidates should come from abroad. The recruitment procedure is currently being finalized, and we can proudly say that we have hired a very nice mix of young, gifted people. There is a high level of diversity, in terms of gender, geographic roots, and academic background.

NETWORKS-COFUND 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
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
Benedikt Meylahn	The dynamics of trust networks	Michel Mandjes, 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

After receiving the COFUND for these 14 PhD positions, NETWORKS has been granted a COFUND grant of €1.0 million to appoint 14 postdoctoral researchers for 2 years early 2021.
Also this time we received very positive feedback from the evaluation committee. They praised the quality of the research options within NETWORKS and the way NETWORKS is organized: “the proposal convincingly demonstrates that the fellows will be excellently prepared for high-level positions in academia and industry”.

In fall 2021 a first call for 8 positions out of 14 positions was opened, leading to 6 appointments. A second call will open in 2022.

DATA-DRIVEN QUEUEING CHALLENGES (DDQC) 2021

In September NETWORKS organized DDQC 2021 in collaboration with the ARC Centre of Excellence for Mathematical & Statistical Frontiers (ACEMS) and the Alan Turing Institute. This online workshop brought together researchers with backgrounds in statistics, stochastic modelling, data science and control to discuss contemporary queueing theory challenges. The program targeted at audiences in three continents (Australia, Europe and the Americas).

Therefore the workshop sessions were scheduled in a way that each participant was able to follow 4 out of 6 sessions in real time. Additionally, all presentations were recorded. We received very positive feedback — there was a clear need for a workshop revolving around this highly timely theme. We managed to attract top-notch speakers who gave fantastic talks on state-of-the-art methodologies. The event comprised 18 talks with 300 registrants from 25 countries.

EDUCATION

Two main components of the NETWORKS educational program are the Training Weeks and the internships.

In the Training Weeks, researchers from NETWORKS gather to learn more about the research topics studied within the entirety of the NETWORKS project. In the past year, the NETWORKS weeks have been organized on location twice. The first Training Week in 2020 had to be cancelled as it was planned for the beginning of April, just after the first lockdown. For the second Training Week, an online version has been developed. Since online lectures are much more demanding, the week was shortened into four days, starting with a one-hour ‘minicourse’ lecture, which was given by Guido Schaefer (CWI) on the topic of network games. The lecture was followed by 4-6 short research presentations and introductory talks by new PhD students. On the afternoon of the second day there was an online social event to stimulate informal meetings between the Networks members.

The format of the online Training Week was repeated in April 2021. The mini course in this edition was given by Leen Stougie and Ward Romeijnders about approximations in stochastic Integer Programming.
In October 2021 it was possible to organize the Training Week on location. It was great to meet everyone in person. Wonderful minicourses were taught by Daniel Valesin and Mark de Berg. There were quite a few NETWORKS members for whom this was the first time they could in person meet with their peers.

PUBLICATION HIGHLIGHTS

- **Euclidean TSP in narrow strips** Alkema, H. Y., de Berg, M. T. & Kisfaludi-Bak, S., Algorithms, *Geometry and Applications [2003.09948]*, 23 p.
- **Decomposing tournaments into paths** Lo, A., Patel, V., Skokan, J., & Talbot, J., *Proceedings of the London Mathematical Society 121(2)*, pp 426-461
- **The parabolic Anderson model on the hypercube** Avena, L., Gun, O. & Hesse, M., *Stochastic Processes and their Applications 130 (6)*, 3369-3393
- **Complexity of inventory routing problems when routing is easy** Baller, A.C., van Ee, M., Hoogeboom, M., & Stougie, L., *Networks 75(2)*, pp 113-123
- **Quasirandom quantum channels** Bannink, T.R., Briët, J., Labib, F.S., & Maassen, H., *Quantum 4*, pp 298
- **Parameter estimation for multivariate population processes: a saddlepoint approach** de Gunst, M., Hautphenne, S., Mandjes, M., & Sollie, B., *Stochastic Models*, online
- **Local weak convergence for pagerank** Garavaglia, A., van der Hofstad, R. & Litvak, N., *Annals of Applied Probability 30(1)*, pp 40-79
- **Roundabout model with onramp queues: exact results and scaling approximations** Storm, P.J., Bhulai, S., Kager, W. & Mandjes, M., *Physical Review E, Vol. 101 [012311]*
- **Characterizing Policies with Optimal Response Time Tails under Heavy-Tailed Job Sizes** Scully, Z., Van Kreveld, L., Boxma, O., Dorsman, J.-L. & Wierman, A., *Performance Evaluation Review48(1)*, pp 35-36
- **Pass-and-swap queues** Comte, C., & Dorsman, J-P., *Queueing Systems 98*, pp 275—331
- **Vertex deletion parameterized by elimination distance and even less** Jansen, B. M. P., Kroon, J. J. H. D. & Wlodarczyk, M., *STOC 2021 - Proceedings of the 53rd Annual ACM SIGACT Symposium on Theory of Computing.* Khuller, S. & Williams, V. V. (eds.). *Association for Computing Machinery, Inc*, p. 1757-1769 13 p.
- **Hypothesis testing for a Lévy-driven storage system by Poisson sampling** Mandjes, M., & Ravner, L. (2021). *Stochastic Processes and their Applications,* 133, 41-73
-
- **On β-Plurality Points in Spatial Voting Games** Aronov, B., de Berg, M., Gudmundsson, J. & Horton, M., Aug 2021, In: *ACM Transactions on Algorithms.* 17, 3, 21 p., 24.
- **A spectral signature of breaking of ensemble equivalence for constrained random graphs** Dionigi P., Garlaschelli D., Hollander W.T.F. den & Mandjes M. (2021), *Electronic Communications in Probability 26:* 1-15.

ORGANIZATIONAL ASPECTS

ORGANIZATIONAL DEVELOPMENTS

In the reporting period, 14 PhD students were appointed within the NETWORKS program. With these appointments, all PhD positions, including the COFUND positions, have now been filled up.

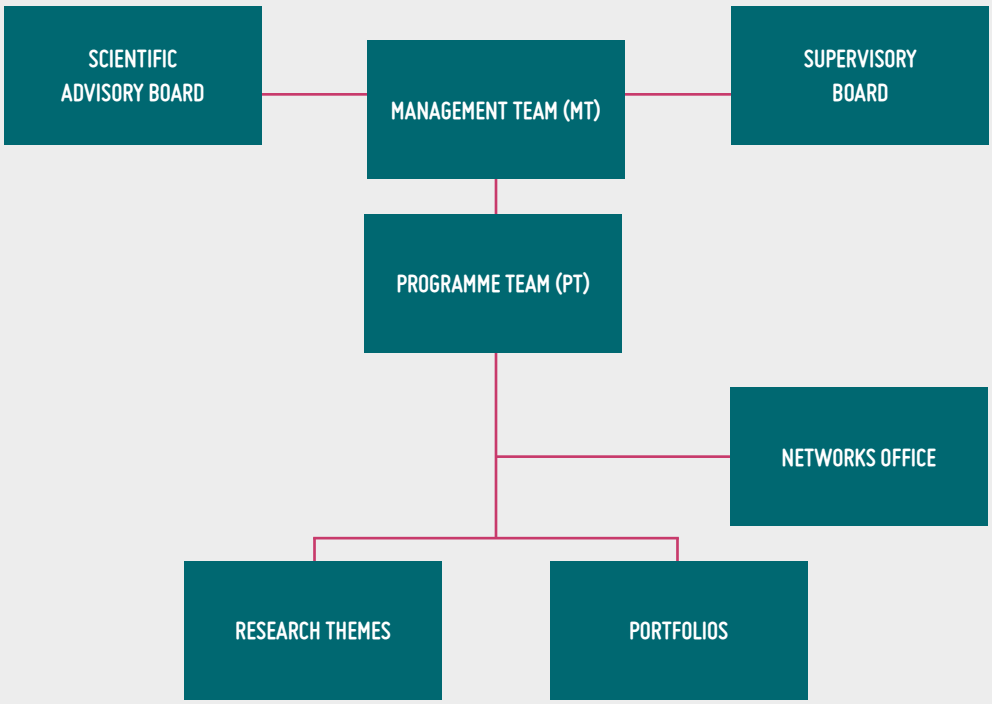
On the level of the project team there were two changes. Ton Koonen (TU/e) retired in 2021; he has been succeeded by Patty Stabile (TU/e). She is expert in large-scale photonic integrated circuits based on semiconductor-optical-amplifiers design for high-capacity nodes for next generation optical networks as well as high-speed electronic control of on-chip integrated systems. Johan van Leeuwaarden (TU/e) has been appointed at Tilburg University; his successor is Nelly Litvak (TU/e and Twente University). She joined TU/e as a part-time full professor in 2017. She is also a visiting professor at Moscow Institute of Physics and Technology. Her background is in applied probability and stochastic operations research. Currently her main research interest is in random graphs, complex networks, and algorithms for complex networks, such as social networks, and the world wide web. Applications include web ranking, community detection, prediction of changes in the world wide web, and prediction of spreading of infections such as COVID-19.

Tim Hulshof (TU/e, tenure track) left the NETWORKS program early 2020. In August 2021 Noela Müller joined the program. Her scientific interests focus on probability theory and statistical physics; in particular on random recursive structures, inference on random graphs, correlations and phase transitions.

By the end of 2021, NETWORKS counted 57 members and 51 affiliated members (who are not paid by the grant yet strongly connected to the NETWORKS program). See page 28 for a complete overview of the NETWORKS members.

NETWORKS members and affiliated members convene two times a year during the so-called NETWORKS days. The first NETWORKS day, scheduled for March 2020, was cancelled. We developed an online alternative by organizing a monthly seminar with one keynote lecture and short introduction presentations of the new NETWORKS members. The first edition of this online seminar was held in May 2020. The online seminar series have been continued until the end of 2021. Although they felt as surrogate, they definitely served the purpose of keeping the community connected. Another way to maintain the community feeling was the organization of online social events, like a wood burning and painting workshop.

ORGANOGRAM



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NETWORKS OFFICE
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Patty Koorn, workshop officer
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Quantum networks
Dynamics of networks
Dynamics on networks
Transportation and traffic networks
Communication and energy networks

AWARDS AND GRANTS

AWARDS

Royal distinction

Ton Koonen was appointed full-time professor of Broadband Networks at the Department of Electrical Engineering at Eindhoven University of Technology (TU/e) on January 1, 2001, and officially retired on February 20, 2021. He delivered his valedictory lecture entitled 'Light work(s)' on September 24, 2021. During the event Koonen received a royal distinction and received the decoration of a Knight of the Order of the Netherlands Lion.

Gijs de Leve prize for best PhD thesis in Operations Research

Pieter Kleer, former NETWORKS PhD student, has been awarded the Gijs de Leve Prize 2018-2020. He received the prize on 22 January 2021 on the occasion of the annual congress of the LNMB, the Dutch Network on the Mathematics of Operations Research. In awarding Pieter Kleer this prestigious prize, the jury recognized his PhD thesis as the 'best PhD thesis in the area of Mathematics of Operations Research defended in the last three years'.

Applied Probability Trust Prize 2020

On January 16th Fiona Sloothaak (TU/e) successfully defended her PhD thesis entitled "Criticality in Power Networks: A Probabilistic Approach". In recognition of the superb quality of this thesis Sloothaak received the 2020 Applied Probability Trust Prize. The Trust Prize is a highly selective honor awarded to young researchers for excellent scientific achievements.

INFORMS Markov Lecturer 2020

Sem Borst (TU/e) was invited to give the Markov Lecture 2020 for the Applied Probability Society, a subdivision of the Institute for Operations Research and the Management Sciences (INFORMS). Borst was the first researcher from a Dutch university to present the lecture since it was established in 2005. The Markov Lecturer is selected by the APS prize committee. The aim is to both honor the associated speaker and bring to the APS membership topical work of the highest calibre.

EATCS Distinguished Dissertation Award

Former NETWORKS PhD student Sándor Kisfaludi-Bak (TU/e) was awarded the Distinguished Dissertation Award of the European Association for Theoretical Computer Science (EATCS), an international organization whose goal is to promote theoretical computer science, to facilitate the exchange of ideas and results among theoretical computer scientists, and to stimulate cooperation between the theoretical and the practical community in computer science. Sándor received his PhD cum laude from TU/e, where he did his research co-supervised by Mark de Berg and Hans Bodlaender.

GRANTS

NETWORKS consortium

MSCA COFUND grant for 14 postdoctoral fellowships

NETWORKS consortium

MSCA COFUND grant for 14 PhD positions

NWO VICI grant

Johan van Leeuwaarden

NWO – GROOT grant

o.a. Leen Stougie, Nikhil Bansal, Monique Laurent

PHD DEFENCES

PHD STUDENT	DEFENCE DATE	UNIVERSITY	THESIS TITLE	PROMOTORES
Fiona Sloothaak	16 January 2020	TU/e	Criticality in power networks – a probabilistic approach	Bert Zwart, Sem Borst
Tom Bannink	30 January 2020	UvA / CWI	Quantum and stochastic processes	Harry Buhrman, Frank den Hollander
Bart Post	26 February 2020	TU/e	Load-driven self-organization of Radio-over-Fibre enabled dense cellular networks	Ton Koonen, Sem Borst
Lorenzo Federico	9 March 2020	TU/e	Phase transitions and connectivity in random graphs	Remco van der Hofstad, Frank den Hollander
Mariska Heemskerk	23 October 2020	UvA	Overdispersion in Service Systems	Michel Mandjes, Johan van Leeuwaarden
Matteo Sfragara	28 October 2020	UL	Wireless Random-Access Networks and Spectra of Random Graphs	Frank den Hollander, Sem Borst, Francesca Nardi
Madelon de Kemp	15 December 2020	UvA	Performance bounds in stochastic scheduling problems	Michel Mandjes, Neil Olver
Jaap Storm	2 February 2021	VUA	Asymptotic Analysis, Stability and Applications	Sandjai Bhulai, Michel Mandjes
Mark van der Boor	26 March 2021	TU/e	Hyper-Scalable Load Balancing	Sem Borst, Johan van Leeuwaarden
Birgit Sollie	7 June 2021	VUA	Statistical inverse problems for population processes	Michel Mandjes, Mathisca de Gunst
Daniel Olah	9 July 2021	TU/e	Reliable Geometric Spanners	Kevin Buchin, Júlia Komjáthy
Margriet Oomen	18 November 2021	UL	Spatial populations with seed-bank	Frank den Hollander, Andreas Greven
Youri Raaijmakers	1 December 2021	TU/e	Job-Replication Trade-Offs: Performance Analysis of Redundancy Systems	Sem Borst, Onno Boxma

NETWORKS MEMBERS

NAME	FUNCTION PROFILE	AFFILIATION
Henk Alkema, MSc	PhD	TU/e
Dr. Elene Anton	Postdoc	TU/e
dr. Luca Avena	Asst. professor	UL
prof.dr. Mark de Berg	Professor	TU/e
Bharti, MSc, MPhil	PhD	UvA
Wessel Blomerus, MSc	PhD	TU/e
Mark van der Boor, MSc	PhD	TU/e
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	CWI
prof.dr. Harry Buhrman	Professor	UvA, CWI
Federico Capannoli, MSc	PhD	UL
dr. Suman Chakraborty	Postdoc	TU/e
Tiny Dekker	Support Staff	UvA
Pierfrancesco Dionigi, MSc	PhD	UL
dr. Jan-Pieter Dorsman	Asst. professor	UvA
Tim Engels, MSc	PhD	TU/e
Francisco Escudero, MSc	PhD	CWI

NAME	FUNCTION PROFILE	AFFILIATION
Hans de Ferrante, MSc	PhD	TU/e
Diego Goldsztajn, MSc	PhD	TU/e
Martijn Gösgens, MSc	PhD	TU/e
Rowel Gündlach, MSc	PhD	TU/e
Mariska Heemskerk, MSc	PhD	UvA
prof.dr. Remco van der Hofstad	Professor	TU/e
prof.dr. Frank den Hollander	Professor	UL
dr. Tim Hulshof	Asst. professor	TU/e
dr. Bart Jansen	Asst. professor	TU/e
Dr. Mark Jones	Postdoc	CWI
Purva Joshi, MSc	PhD	TU/e
Rens Kamphuis, MSc	PhD	UvA
dr. Stella Kapodistria	Asst. professor	TU/e
Madelon de Kemp, MSc	PhD	UvA
Ellen Konijnenberg	Support Staff	TU/e
prof.ir. Ton Koonen	Professor	TU/e
Patty Koorn	Support Staff	TU/e
Twan Koperberg, MSc	PhD	UL
Gianluca Kosmella, MSc	PhD	TU/e
dr.ing. Marieke Kranenburg	Support Staff	UvA

NETWORKS MEMBERS

NAME	FUNCTION PROFILE	AFFILIATION
Lucas van Kreveld, MSc	PhD	UvA
Farrokh Labib, MSc	PhD	CWI
Boris Lebedenko, MSc	PhD	UvA
prof.dr. Johan van Leeuwaarden	Professor	TU/e
Nikki Levering, MSc	PhD	UvA
prof.dr. Nelly Litvak	Professor	UT
Andrés López Martínez, MSc	PhD	TU/e
Roshan Mahes, MSc	PhD	UvA
Nandan Malhotra, MSc	PhD	UL
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prof.dr. Sindo Núñez Queija	Professor	UvA
Daniel Olah, MSc	PhD	TU/e
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NAME	FUNCTION PROFILE	AFFILIATION
Manish Pandey, MSc	PhD	TU/e
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Mehmet Akif Yildiz, MSc	PhD	UvA
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Dr. Martín Zubeldía	Postdoc	TU/e

NET
WORKS

by address: University of Amsterdam
Faculty of Science – Korteweg-de Vries Institute
PO Box 94248
1090 GE Amsterdam
the Netherlands
+31 (0)20 525 6499
info@thenetworkcenter.nl
www.thenetworkcenter.nl

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