

# NET WORKS

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 2014



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# INTRODUCTION

**Transportation, traffic, communication and energy networks form the backbone of our modern society. To deal with the uncertainty, variation, unpredictability, size and complexity that are inherently present in these large-scale networks, it is essential to develop radically new ways of thinking. The NETWORKS programme is aimed at addressing this pressing challenge. Its ultimate goal is to develop novel techniques in mathematics and computer science that help to design highly reliable networks and effectively monitor and control them. At the methodological level, the programme primarily exploits stochastics and algorithmics, focusing on modelling, understanding, controlling and optimizing networks that are intrinsically complex and highly volatile. Our objective is to have developed, by the end of the project, mathematical tools that facilitate self-organizing and intelligent networks.**

NETWORKS started in the summer of 2014 as a 10-year programme funded by the Dutch Ministry of Education, Culture and Science through the Netherlands Organisation for Scientific Research (NWO), hosted by the University of Amsterdam (UvA), Eindhoven University of Technology (TU/e), Leiden University (UL), and the Center for Mathematics and Computer Science (CWI) in Amsterdam.

NETWORKS' first year has been used to set up the programme's scientific and organizational structure, and to facilitate the interaction between the partners. Hiring staff was one of the key elements. On the basis of the project plan, 15 NETWORKS-funded PhD projects were defined, as well as 8 projects funded from the partners' matching resources. By assigning two supervisors to each project, a structure was chosen that

NETWORKS PROJECTTEAM



Mark de Berg  
 Sem Borst  
 Onno Boxma  
 Harry Buhrman  
 Remco van der Hofstad  
 Frank den Hollander  
 Ton Koonen  
 Johan van Leeuwen  
 Michel Mandjes  
 Lex Schrijver  
 Johan van Leeuwen  
 Gerhard Woeginger

optimally stimulates the interaction between members of different participating institutions on the one hand, and between the areas of algorithmics and stochastics on the other.

The second major hiring effort concentrated on attracting promising young researchers to seven tenure-track positions. For five of these, highly talented scientists have already been hired, while for the other two a selection is currently being made from the very strong applications that were received. Through these new tenure-track appointments, NETWORKS structurally contributes towards enlarging the population of permanent staff in mathematics and computer science in the Netherlands. In addition, 5 postdocs were hired or will be hired in the near future.

The interaction with colleagues at the participating institutes that were initially not involved in the proposal has been further intensified, typically by assigning them the role of co-supervisors in the PhD projects (the so-called “Affiliated members”). In this respect, it is worth mentioning that the VU University Amsterdam contributes to NETWORKS by funding two PhD projects.

A major theme in the first year was the development of an educational programme. This has been set up essentially to serve several objectives: firstly to train the PhD students, thus supporting their research, secondly to bridge the knowledge gap between researchers from stochastics and algorithms, and thirdly to further increase the community feeling among all NETWORKS members. The idea is to organize three training weeks in the coming two years, the first of which will take place summer 2015. In addition PhD students will do an internship in a research group from a different area.

In terms of outreach activities, important steps have been made as well. The NETWORKS programme has been highly visible, with members having been involved in various public lectures. The next step will be the appointment of a dedicated outreach staff member. Also, the process of setting up the “Network pages”, a web-portal to NETWORKS-related research aimed at a broad audience, has been initiated.

At all partner institutions, NETWORKS has spurred various new initiatives and spin-offs. For instance, in Leiden joint projects and activities with physics and biology have been initiated, as well as a joint one-semester course on “Complex Networks” for Master’s students and a monthly lecture series. At UvA it is being explored whether there should be a Master’s track about networks, as seen from an operations research perspective. At TU/e Algorithmics and Stochastics has been chosen as one of the four research themes on which the department wants to focus.

This annual report provides an overview of the NETWORKS activities in 2014: the programme’s first year. The NETWORKS team is eager to keep you informed about its scientific progress in the years to come.

*Michel Mandjes*

KICKOFF NETWORKS



De Bazel, Amsterdam

**WITH A KICKOFF EVENT ON JUNE 20TH, NETWORKS CELEBRATED ITS SCIENTIFIC START. THE MEETING WAS HELD IN “DE BAZEL” IN AMSTERDAM.**

Michel Mandjes, the programme leader, started by giving an overview of NETWORKS’ plans and ambitions. After this introduction, two leading researchers were invited to present their view on the future of complex networks, from a stochastic and algorithmic perspective. David Gamarnik, professor of Operations Research at MIT Sloan School of Management (Cambridge MA, United States), introduced the audience to a selection of intriguing queueing-motivated examples and their mathematical background. Kurt Mehlhorn, director of the Max Planck Institute for Computer Science (Saarbruecken, Germany), spoke about appealing self-organization phenomena in biological networks, and gave his view on the NETWORKS research agenda.

After these lectures, Dymph van den Boom, Rector Magnificus of the University of Amsterdam, and Arjen Doelman, chairman of NWO Physical Sciences, gave their visions on the opportunities for NETWORKS, and for mathematics and computer science in the Netherlands in general. After this more formal part, there was a tour through the building and a walking dinner.

Among the almost 100 attendees were representatives from the Ministry of Education, Culture and Science (OC&W), the Netherlands Organisation for Scientific Research (NWO), and the Platform Wiskunde Nederland (PWN).



Kurt Mehlhorn



David Gamarnik



Walking dinner

# RESEARCH THEMES

The background of the page is a dark teal color. It features a complex network diagram composed of numerous thin, light pink lines that intersect and branch out across the page. At various points where these lines meet, there are small, solid pink circular nodes. The overall pattern is dense and interconnected, resembling a circuit board or a data network map. The text 'RESEARCH THEMES' is centered in the upper half of the page in a white, sans-serif font.

**NETWORKS consists of 7 research themes, each covering a number of key questions that zoom in on the challenging mathematical problems underlying complex large-scale networks. Within each of these themes several smaller research projects are distinguished, on which PhD students and postdocs have been (or will be) appointed. The themes are chosen in such a way that they focus on a specific issue, but they are evidently interrelated in many ways. For instance Themes 6 and 7, focusing on applications, will heavily rely on results developed in the other themes, but at the same time, Themes 6 and 7 will pose new questions to be dealt with in those other themes.**

## THEME 1: APPROXIMATE NETWORK METHODS

### INTRODUCTION

The design, optimization, and control of networks involves a large variety of challenging algorithmic problems. How to compute the shortest tour that visits all nodes in the network? How to find the minimum number of nodes in the network that together can monitor all links? How to decide whether two networks have the same structure? Unfortunately, many of these problems are Non-deterministic Polynomial-time hard or “NP-hard”: there are no efficient algorithms that solve these problems optimally on all possible instances (unless  $P=NP$ ). Nevertheless, NP-hard network problems need to be dealt with in practice.

### PROJECTS AND PROGRESS

- The goal of the first project in this theme is to develop novel techniques for dealing with NP-hard network problems along several lines of attack. An important one is to use the fact that in practice it is

often good enough to have an approximation algorithm, which is guaranteed to compute solutions that are very close to the optimal solution. The research in this direction will be further strengthened through a TOP-grant of Nikhil Bansal and Monique Laurent (both affiliated NETWORKS members) and Ronald de Wolf.

- Another branch of research exploits 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. This idea underlies so-called FPT algorithms. With the appointment of Bart Jansen (on a tenure-track position) and Hans Bodlaender (as part-time full professor), both at the TU Eindhoven, NETWORKS has attracted two experts in this area. In the mean time, Jansen obtained a NWO-Veni grant, and two PhD projects will start on FPT algorithms in the coming year to further boost the activities in this area. Furthermore, in 2015 Viresh Patel will start on a tenure-track position at UvA.
- To foster the collaboration within NETWORKS, Jansen (TU/e) spent two months at CWI to work with Harry Burhman (CWI). As a result, a joint PhD project is scheduled to start in 2015.

## THEME 2: SPATIAL NETWORKS

### INTRODUCTION

In many applications the networks under consideration are geometric networks, i.e., every node has a location in some geometric space and the edges are represented by connections between the nodes. An example is a railway network, where nodes correspond to stations and edges to railway



tracks. Another example is a large molecule, 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 behaviour 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 exploring geometric properties is that of the travelling salesman.

### PROJECTS AND PROGRESS

- Supervised by Mark de Berg and Gerhard Woeginger, Aleksandar Markovic started his PhD project at TU/e on algorithmic problems related to range and frequency assignment in wireless networks. In an abstract setting, such assignment problems can often be modelled as problems on intersection graphs, that is, graphs whose nodes correspond to disks (or other regions) in the plane and whose edges connect intersecting disks.
- Lorenzo Federico, under supervision of Remco van der Hofstad, Frank den Hollander and NETWORKS tenure-tracker Tim Hulshof, has started investigating critical percolation and minimal spanning trees on spatial graphs. Percolation is obtained by keeping or removing edges independently, and displays a phase transition in its connectivity structure. The minimal spanning tree of a weighted graph is the tree that spans all the vertices and has minimal sum of weights. Interestingly, these two problems are closely related. Federico will start by investigating under what conditions percolation on finite spatial graphs behaves in a similar way as its non-spatial (and more widely investigated) analogues.
- In the project “Dynamic behaviour of interacting-particle systems with hard-core interaction”, supervised by Sem Borst, Frank den Hollander and Francesca Nardi, the PhD-vacancy has not yet been filled. Postdoc Siamak Taati (Leiden) joined the project in December 2014. The aim of this project is to investigate how competition for shared resources among contending nodes in communication networks can be modelled in terms of interacting-particle systems with hard-core interaction on conflict graphs. Performance characteristics in highly loaded settings are controlled by metastability effects. With the help of potential theory of Markov processes, a general theory has been developed that applies to arbitrary networks and that requires the identification of a number of intricate model-dependent quantities. For special classes of bi-partite graphs these quantities have been computed.
- In March-April 2015 a Stochastic Activity Month (SAM) on random walks in random environments will be held at Eurandom with Luca Avena, Hulshof and van der Hofstad as co-organizers; it will be partly sponsored by NETWORKS.

## THEME 3: QUANTUM NETWORKS

### INTRODUCTION

Quantum computers are based on the laws of quantum mechanics. Its basic building block is a quantum bit, or qubit, which can be simultaneously 0 and 1 due to the superposition principle of quantum mechanics. Whenever a qubit is added to a system, the number of states doubles: with  $n$  qubits a

quantum system can be realized that is a superposition of  $2^n$  classical states. A quantum computer can operate on all these classical states simultaneously, thus allowing for massive parallel computing. Unfortunately, there is a catch: whenever the final quantum state is observed, the measurement postulate of quantum mechanics dictates that it collapses to a random classical state, destroying the superposition.

In some cases, by employing smart quantum algorithms, interference can be used to cancel out the uninteresting computations, while enhancing the computations that carry the desired outcome. This is the idea behind Shor's quantum algorithm for factoring numbers into their prime factors. This algorithm in turn breaks most of modern cryptography, whose security is based on our inability to efficiently perform the factorization task. Not all algorithmic problems are amenable to a quantum speed-up like the factorisation problem. One of the key open questions is which computational problems allow for such a speed-up and which are hard even for a quantum computer. NETWORKS theme 3 deals with networks in the quantum setting.

### PROJECTS AND PROGRESS

- Harry Buhrman and Frank den Hollander looked at the quantum analogue of classical random walks: quantum walks on specific network topologies. To start, they focused on a linear network where the environment is random as well. They obtained preliminary insights into how a proper model should be set up and are in the process of hiring a PhD student to continue work on this topic.
- A small workshop on the topic at the Lorentz Center is to take place in December 2015, bringing together both the classical random walk and the quantum random walk communities.

## THEME 4: DYNAMICS OF NETWORKS

### INTRODUCTION

Virtually all sectors of society are faced with issues regarding the design, operation and control of highly complex networks. NETWORKS theme 4 specifically focuses on networks that evolve over time, in a way that is typically 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 behaviour can be captured and analyzed.

### PROJECTS AND PROGRESS

- In August 2014, Souvik Dhara started on the project "Information diffusion and epidemics on random graphs". Dhara is supervised by Remco van der Hofstad and Johan van Leeuwen, and works on critical epidemics on the configuration model, one of the most popular and most important mathematical models for network structures of large-scale complex networks such as social networks and the internet. This is also joint work with Sanchayan Sen, who started in September 2014 as a postdoc on the related topic of "Universality for metric convergence of random graphs and minimal spanning trees."
- In August 2014, Debankur Mukherjee started on "Hard-core interaction models on dynamic graphs", supervised by Sem Borst and Johan van Leeuwen. Mukherjee investigates graph structures in continuous spaces, in particular, networks that consist of repelling particles, which give rise to intricate time-varying behaviour in terms of network structure and network performance.

- The project “Correlated sources in networks” was started with a talented master student, Mariska Heemskerk, who under the supervision of Michel Mandjes and Johan van Leeuwen is finalizing her Master’s thesis. Heemskerk will continue her research on this topic as a PhD student starting September 2015. Her research focuses on systems operating under overdispersion, experiencing higher intrinsic variability than in traditional Poissonian models.
- The project “Sparse graph limits and statistical mechanics” has been formulated by Remco van der Hofstad and Lex Schrijver, and still has an open vacancy.
- A final project, “Random processes on dynamic random graphs” will be taken up in April 2015 by PhD student Hakan Guldás, who was recently hired and will be supervised by Frank den Hollander, Remco van der Hofstad and Luca Avena.
- In line with the plans outlined in the project plan, satellite projects and matching positions are set up in which the results from NETWORKS are translated into more applied settings. In January 2015, Alessandro Garavaglia started to investigate citation networks. Garavaglia is supervised by Gerhard Woeginger and Remco van der Hofstad, and will match theoretical analysis with empirical data of citation networks, for example from the arXiv.
- In December 2014, Remco van der Hofstad and Johan van Leeuwen obtained an NWO TOP grant for a topic related to the project “Information diffusion and epidemics on random graphs”, but focused more on epidemic processes on networks with communities.

## THEME 5: DYNAMICS ON NETWORKS

### INTRODUCTION

Complex networks are carriers of dynamics. Mathematical theory in this area is scarce. So far the focus has been on random processes



### PROFILE NICOS STARREVELD

#### WHAT IS IT THAT MAKES NETWORKS ATTRACTIVE TO YOU?

What I find attractive in NETWORKS, apart from the numerous opportunities to learn, is the fact that my PhD is part of a broader project. To have the chance to participate in workshops and do an internship in a research group outside of my field of research is something I find fascinating about NETWORKS. Last but not least, the elective activities in which PhD students may participate is something unique; it allows us to see how a research project is built and organized.

#### WHAT IS YOUR RESEARCH TOPIC WITHIN NETWORKS?

My research is centred around queueing systems. At the moment our main point of interest is the transient behaviour of some queueing models.

#### HOW DID YOU EXPERIENCE THE FIRST MONTHS OF THE NETWORKS PROGRAMME?

During the last 5 months I had the chance to meet most of the NETWORKS people and exchange some ideas with them. This gave birth to ideas which may turn out to be interesting research topics.

#### HOW DO YOU EXPERIENCE WORKING IN THE NETHERLANDS?

Not that I have working experience in other countries but working in the Netherlands is a very pleasant experience. Although sometimes I miss the strict working conditions, fixed time schedule, regular evaluations etc. During the first 6 months of my PhD I had the opportunity to learn and develop skills that will help me in the future.

that are well understood in regular networks, such as random walks, percolation, contact processes and Glauber dynamics. The main challenge is to understand how the behaviour of such processes is affected by the irregular structure of the network, in particular, the presence of “hubs”. It is believed that local conservation laws in the dynamics play a crucial role in determining the global behaviour.

### PROJECTS AND PROGRESS

- The project “Metastable behaviour of random graphs” started in September 2014, with postdoc Oliver Jovanovski and supervisors Frank den Hollander and Francesca Nardi. Since January 2015, Sander Dommers (Bologna) has joined the project. Research has focused on Glauber spin-flip dynamics on random graphs with prescribed degree sequences (configuration model). Initially all spins point downwards, a positive magnetic field is switched on, and spins are allowed to flip up and down according to a Metropolis dynamics associated with an Ising-spin Hamiltonian. The interest is in determining the time until all spins point upwards. It turns out that for low temperature the critical droplet triggering the crossover from “all minus” to “all plus” is very large, about half the size of the graph. This is markedly different from what is seen in regular graphs.
- On the project “Breaking of ensemble equivalence for complex networks” PhD student Andrea Roccaverde has been appointed under the supervision of Diego Garlaschelli and Frank den Hollander. It is generally believed that, for physical systems in the thermodynamic limit, the microcanonical description as a function of energy coincides with the canonical description as a function of temperature. However, various examples have been identified for which the microcanonical and canonical ensembles are not equivalent. A complete theory of this intriguing phenomenon is still missing. The researchers found that ensemble nonequivalence can manifest itself also for graphs with topological constraints, in particular, graphs with a given degree sequence. This mathematical result provides a theoretical explanation for various “anomalies” that have recently been observed in real-world networks.
- At the UvA, PhD student Nicos Starreveld was appointed on the project “Interpretation of measurements for distributed control”, supervised by Rene Bekker (VU) and Michel Mandjes. In a first paper, transient analysis of Levy-driven queues is pursued, which helps assessing the quality of specific classes of estimators. At the same time it is explored how to build a new methodology, based on techniques developed by Mandjes and Den Boer (in the paper “Convergence rates of Laplace-transform based estimators”).

## THEME 6: TRANSPORTATION AND TRAFFIC NETWORKS

### INTRODUCTION

Virtually all sectors of society are faced with issues regarding the design, operation and control of highly complex networks. This research theme specifically focuses on a key application area that is of crucial societal interest, namely, transportation and traffic networks.

Several network-related problems are studied. In some of these the network structure is fixed, while in others the objective is the shaping of the network structure. The emphasis is both on structure-related issues (planning and dimensioning of transportation and traffic networks) and the operations on

existing networks (routing and scheduling and other traffic management mechanisms that relate to shorter time scales).

### PROJECTS AND PROGRESS

In the first year of the project emphasis has been on problems related to enforcing smooth merging of traffic streams on highways. Sindo Nunez-Queija and Michel Mandjes at UvA, and Marko Boon and Onno Boxma at TU/e are actively involved in defining and solving problems revolving around this theme. Queueing theoretic models are being developed to model the dynamics of the waiting time process at the ramp; interestingly, non-trivial stability conditions are identified. At this project one PhD student has been appointed at UvA: Abishek.

- At the same time, in the VU matching compartment of NETWORKS a project has been defined in which the effect of traffic control measures will be quantified, relying on a broad range of techniques, ranging from simulation and Markov decision processes to cellular automata. Vera Rensink, who is currently working towards a master thesis on this topic, will start as PhD student in 2015 and will be supervised by Sandjai Bhulai, Wouter Kager and Mandjes.
- In line with the plans outlined in the project plan, satellite projects were set up in which the results from NETWORKS are translated into more applied settings. One such project is DYNAFLOAT, funded by the Top consortium for science and innovation (TKI) and NWO; the academic partners involved are CWI, TU/e and UT. Also an interaction with Delft University of Technology (TUD; Bart van Arem and Serge Hoogendoorn, Department of Transport & Planning) was initiated.

## THEME 7: COMMUNICATION AND ENERGY NETWORKS

### INTRODUCTION

Communication and energy networks are both prominent examples 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. Mathematically, the uncertainty and random variation may be described in terms of networks with massive numbers of nodes with activity rates that fluctuate over time.

### PROJECTS AND PROGRESS

In the first year of this NETWORKS theme, the activities have revolved around three specific research topics as further described below:

- Onno Boxma, Ton Koonen and Jacques Resing (all at TU/e) have pursued the analysis and optimization of the performance of optical network switches. Murtuza Ali Abidini has started as a PhD student on this project at TU/e on October 1, 2014, with a formal appointment in the Department of Mathematics and Computer Science and strong engagement with Koonen in the Electrical Engineering Department. Abidini, Boxma and Resing have conducted a preliminary investigation of the buffer dynamics in optical network switches with delay loops based on vacation queues and polling models with glue periods and retrials, and plan to further pursue various extensions and refinements.

- Sem Borst, Ton Koonen and Gerhard Woeginger (all at TU/e) have initiated the design of efficient algorithms for dynamic resource allocation and user association in wireless radio-fiber pico-cell networks. Specifically, the goal is to develop distributed algorithms for assigning transmission frequencies and power levels and exploit multi-wavelength routing techniques to enable coordinated dynamic capacity allocation. Bart Post has started as a PhD student on this project at TU/e on November 1, 2014, with a formal appointment in the group of Koonen in the Electrical Engineering Department and extensive involvement in the NETWORKS activities within Department of Mathematics and Computer Science. An exploratory meeting has been held with Hans van den Berg (TNO) to discuss common interests and explore the scope for possible joint efforts.
- Sem Borst (TU/e), Sindo Nunez-Queija (UvA/CWI) and Bert Zwart (CWI/TU/e) have launched a research thread focusing on dynamic interaction and volatility in future energy networks, motivated by the random variation and uncertainty induced by the rising deployment of renewable energy sources. In particular, the initial efforts will centre on examining how random link failures caused by rare events can cascade through a power network, depending on the topology and spatial supply and demand patterns. Fiona Sloothaak has been recruited to join the project as a PhD student at TU/e on April 1, 2015. There are plans to seek funding for a satellite project addressing reliability issues from a joint probability and optimization perspective.



## PROFIEL BART POST

### WHAT IS IT THAT MAKES NETWORKS ATTRACTIVE TO YOU?

First of all, I am fascinated by applications of graph theory and this is most obvious in anything that represents a network. Moreover, I enjoy working on the boundary between mathematics and technology, which is where many network problems live. Lastly the feel of a mathematical community centred around networks really appeals to me because you can work together with many people.

### WHAT IS YOUR RESEARCH TOPIC WITHIN NETWORKS?

The name of my project is "Dynamic resource allocation and user association in Pico-Cell networks". Consider replacing

one large mobile communication base station by many small ones, connected by the use of optical fibers as backhaul. I will look into what smaller antennas operate on which frequencies (resource allocation), which user communicates with which antenna (user association). Moreover, it is expected that this approach will save energy (by decreasing the transmitting distance) and I will look into how much energy can be saved by this approach.

### HOW DID YOU EXPERIENCE THE FIRST MONTHS OF THE NETWORKS PROGRAMME?

It was impressive to immediately enlarge my own academic network by all the

NETWORKS people. I feel being part of something bigger than only my own research, contributing to the efforts of a whole group of researchers.

### HOW DO YOU EXPERIENCE WORKING IN THE NETHERLANDS?

I love the fast and direct way of working with each other. This may come as no surprise since I am Dutch myself. Also, I feel that even though we are a small country, we are on the frontier of mathematical and technical research, creating new innovations every day.

# PORTFOLIOS

## NETWORK PAGES: AN INTERACTIVE NETWORKS WEBSITE

Within the NETWORKS project, an interactive web site concerning networks will be launched, aiming at fellow researchers with a multidisciplinary background and a shared fascination for networks, but also at high-school students, teachers and lay people. Setting up this website is still in the preliminary phase, since it was decided to start full-fledged in the summer of 2015, letting other start-up activities of NETWORKS take priority.

In the summer of 2015 Robert Fitzner will start as a scientific programmer for 4 years; 2.5 years of his appointment will be paid by NETWORKS, 1.5 years will be covered by the Institute for Complex Molecular Systems (ICMS) at TU/e. This also forges interaction between this strong multidisciplinary institute and NETWORKS.

In the meanwhile an editorial board was formed, currently consisting of Mark de Berg and Tim Hulshof and Bart Post, with chair Remco van der Hofstad. This board will determine the set-up of the 'Network Pages'. To this end, a questionnaire will be held among the NETWORKS staff about possible subjects for the 'Network Pages'. The aim is to have a first version of the website up and running in the summer of 2016.

## OUTREACH

In 2014 various outreach activities have taken place. In fact, the kick-off at "De Bazel" in June 2014 was the first of these events; there, the programme was presented to a broad audience consisting of e.g. representatives of the four participating partners UvA, TU/e, CWI and UL, industrial partners, administrative support, representatives of NWO and OCW, etc.

Apart from that, members of the project team delivered talks for non-experts at various occasions, such as Spui25 (Mandjes), a Cleveringa-lecture (den Hollander), a KNAW theme evening (Van der Hofstad, Den Hollander, Mandjes), Youth lecture Museum Boerhaave (Schrijver); these public lectures were attended by large audiences of interested laymen.

In addition, Mandjes, Van Leeuwen, and Van der Hofstad have been interviewed on national public radio. Mandjes and Van Leeuwen are involved in setting up, jointly with Jan van Neerven, a special issue of "Nieuw Archief voor Wiskunde" on the mathematics (and computer science) of networks.

It is expected that the outreach activity will gain momentum in 2015; much of our efforts in 2014 targeted at exploring the optimal infrastructure to foster this (e.g., by inter-

### WORKSHOPS

In 2014 NETWORKS supported and co-organised the following workshops:

- "Stochastic Networks", 23-27 June 2014, Amsterdam.
- "Performance and Control of Large-Scale Networks", 30 June - 2 July 2014, Eurandom.
- "The 21st International Symposium on Mathematical Theory of Networks and Systems" (MTNS 2014), 7-11 July 2014, Groningen.
- "Rare Events, Large Deviations, Efficient Importance Sampling" (RESIM2014), 27-29 August 2014, Amsterdam.



viewing various Dutch outreach experts). Within the NETWORKS team, Mandjes and Van Leeuwen coordinate the outreach actions. NETWORKS is in the process of hiring an outreach professional, who will help the programme to become more visible.

## EDUCATION

To set up the NETWORKS educational programme, an Education Committee was established. The committee has five members from different institutions and with different scientific backgrounds: Luca Avena, Mark de Berg, Aleksandar Markovic, Nicos Starreveld and Johan van Leeuwen. De Berg acts as chair and serves as a linking pin with the NETWORKS Management Team.

To get an overview of the needs and wishes with respect to educational activities, the committee organized a survey among the NETWORKS researchers. Based on the outcome of the poll and on discussions within the committee and with the MT, the committee developed the NETWORKS educational programme. It consists of training weeks, internships, and mini-courses.

- The training weeks provide knowledge of the basic concepts and techniques from the various areas within NETWORKS and give a flavour of current research topics in those areas. To foster synergy, each training week combines a topic within algorithmics and a topic within stochastics. The weeks are held off-campus so that they also serve to create a community feeling. All NETWORKS PhD students are expected to participate in the training weeks, but the weeks are also open to other NETWORKS researchers. The first training week, on Random Graphs & Computational Geometry, is scheduled for August 2015. Other training weeks (on Stochastic Networks & Optimization



### PROFIEL LUCA AVENA

#### WHAT IS IT THAT MAKES NETWORKS ATTRACTIVE TO YOU?

Our modern world is highly complex. Several biological, social, technological and economical real-systems can be modelled via complex networks, i.e., huge random graphs with highly non-trivial geometry. The systematic study of complex networks has been recently started and can be thought of as a young new science at the interface among mathematics, computer science, physics, economy, biology, sociology. The major goal of this “new science” is to develop a coherent theory aiming to analyze the architecture of real-world complex networks and make predictions about them. The programme NETWORKS aims to boost the development of this “new science”.

#### WHAT IS YOUR RESEARCH TOPIC WITHIN NETWORKS?

My research within NETWORKS mainly concerns the dynamics of networks as well as dynamical processes on networks. More precisely, my main goal is to analyze (1) Markovian dynamics of random graphs, and (2) models of random walks on random evolving graphs; both from a probabilistic/statistical-mechanics perspective. Furthermore, I plan to apply newly developed randomized algorithms in the context of community detection.

#### HOW DO YOU EXPERIENCE WORKING IN THE NETHERLANDS?

I have been travelling and working in several countries (Italy, Germany, France, Switzerland, Brazil, Spain) and I find The Netherlands an excellent country for a scientific career. The following elements, that I find of fundamental importance for an outstanding research environment, characterize quite well my experience in The Netherlands so far: high quality of life, high level of organization, all kinds of facilities, short distances, international environments, open minded people.

and Approximation, and on Statistical Mechanics & Quantum Computing) are scheduled for Winter 2015/16 and Spring/Summer 2016.

- The internships are a second instrument to create synergy and help bridge the gap between stochastics and algorithmics. In their internship, PhD students do a research project in a NETWORKS group from a research area different than their own, or in a company or institution such as TNO. The internships will take 2-3 months and take place in the second or third year of the PhD.
- The mini courses are more specialized and cover advanced and current topics. They will be organized in collaboration between the Educational Committee and the Workshop Committee.

## WORKSHOPS

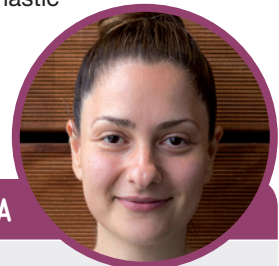
The portfolio “Workshops” is coordinated by Nikhil Bansal, Remco van der Hofstad and Frank den Hollander (chair). This committee has made an inventory of topics that are appropriate for a workshop or a conference organized by NETWORKS. In addition, it has designed a procedure to provide financial support for workshops or conferences on complex networks in general. One route is within existing initiatives such as de Stochastic Activity Month at Eurandom or the Lorentz Center programme. Den Hollander is a member of the scientific advisory committee for the yearly Dutch Mathematical Congresses, and is arranging that NETWORKS organises a special track at the meeting of 2016.

## INTERNATIONALIZATION

One of the goals of NETWORKS is to put the Netherlands in a leading position interna-

tionally by establishing a center for networks research. To reach this goal it is important to collaborate with strong international partners.

- NETWORKS has established a partnership with the University of Bath (UK), through SAMBa (“Statistical Applied Mathematics at Bath”), a doctoral training centre funded by the EPSRC that focuses on modelling of complex stochastic systems. A key component of the activities of SAMBa is a programme of two-week



### PROFILE STELLA KAPODISTRIA

#### WHAT IS IT THAT MAKES NETWORKS ATTRACTIVE TO YOU?

First of all, its multidisciplinary: working on a topic within NETWORKS means that you simultaneously expand your knowledge in both stochastics and algorithmics. Secondly, its world class players: working within a NETWORKS group means you are collaborating with world leading researchers from four research institutions (UvA, TU/e, UL, and CWI). Finally, its state-of-the-art research applications: working for NETWORKS means that you work on novel and innovative topics in the areas of transportation, traffic, communication and energy.

#### WHAT IS YOUR RESEARCH TOPIC WITHIN NETWORKS?

Stochastic operation research on communication and energy networks. In particular, my research interests lie on the field of Applied Probability – Stochastic Processes and Queueing Theory.

#### HOW DID YOU EXPERIENCE THE FIRST MONTHS OF THE NETWORKS PROGRAMME?

It is a very exciting and rewarding experience. I feel that I am constantly evolving in all academic aspects.

#### HOW DO YOU EXPERIENCE WORKING IN THE NETHERLANDS?

The Dutch academic environment is international, diverse and multi-cultural, which makes professional and personal integration very easy.

interactive sessions with industry and other non-academic partners, called ITT (“Integrative Think Tanks”). Members of NETWORKS are invited to participate. Conversely, members of SAMBa are invited to attend workshops organised by NETWORKS. The possibility is being explored of jointly organizing workshops on the topics “Graph Limits” and “Graph Algorithms”. NETWORKS will be participating in an application by SAMBa in 2016 for a RISE-grant within the Marie Curie funding scheme of the EU. This type of funding offers support to build a network between EU research centres and centres from developing countries.

- NETWORKS has invited German researchers from Berlin, Karlsruhe, Munich and Munster to get together and prepare an application for a Transregio SFB (Sonderforschungsbereiche or Collaborative Research Center) with DFG, in which NETWORKS features as a partner. There has been close interaction with German colleagues in the past, so this would be a welcome extension. Coordination of the application lies with the Weierstrass Institute in Berlin.

## VALORIZATION

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: (i) a long-term flux of young talented professionals who are trained in the various groups in NETWORKS;

(ii) active engagement of the various NETWORKS groups in broader efforts to promote the application of advanced knowledge in mathematics and computer science to solve problems of industrial and societal relevance; (iii) close ties maintained by many of the principal investigators in NETWORKS with various companies and societal organizations, and involvement in application-oriented multi-disciplinary projects; (iv) open and high-visibility channels towards companies and societal organizations that face challenges relating to complex dynamic networks and seek innovative solution approaches.

Discussions are ongoing with Evgeny Verbitskiy (UL/Groningen University) to explore opportunities for joint initiatives with the Innovation Committee of the “Platform Wiskunde Nederland” (PWN), in particular in establishing contacts with industry. In addition, NETWORKS is in contact with Van den Berg (TNO) to identify common research interests and joint research efforts around specific topics as well as the scope for a possible broader NETWORKS-wide strategic alliance with TNO, which could provide a prototype for alliances with other strategic partners. Finally, there are opportunities for closer connections with the Dutch Technology Foundation STW and for the participation of NETWORKS at the annual “Studiegroep Wiskunde met de Industrie” event.

Application-oriented projects are typically carried out in the framework of the Topsector themes of the Dutch government, special industrial partnerships or various local initiatives. NETWORKS aims to provide a pipeline of fundamental results fuelling these ‘satellite’ projects and driving long-term innovation, with the DYNAFLOAT project (at CWI, UvA, and TU/e) and Impulse Data Science and Lighting projects (at TU/e) as key current examples.

## SCIENTIFIC HIGHLIGHTS

L. Albertazzi, D. van der Zwaag, C.M.A. Leenders, R. Fitzner, R.W. van der Hofstad and E.W. Meijer:

**PROBING EXCHANGE PATHWAYS IN ONE-DIMENSIONAL AGGREGATES WITH SUPER-RESOLUTION MICROSCOPY.**



**SCIENCE 344(6183): 491-495, (2014).**

Supramolecular fibers are prominent structures in biology and chemistry. In this paper, a quantitative understanding is obtained of the molecular exchange pathways in these one-dimensional aggregates. The presence of non-covalent bonds makes this exchange easier than for linear polymers. We used a combination of super-resolution microscopy (the so-called STORM technique) and stochastic simulation. The potential of this methodology is demonstrated using a set of well-defined synthetic building blocks that self-assemble in a water environment into supramolecular fibrils, and is applied both to biological and synthetic fibers. This work is the result of a collaboration between researchers involved in NETWORKS and members of the Institute for Complex Molecular Systems at TU/e.

Harry Buhrman, Richard Cleve, Michal Koucký, Bruno Loff, Florian Speelman:

**COMPUTING WITH A FULL MEMORY: CATALYTIC SPACE.**

**STOC 2014: 857-866**

Imagine the following scenario. You want to perform a computation that requires more memory than you currently have available on your computer. One way of dealing with this problem is by installing a new hard drive. As it turns out you have a hard drive but it is full with data, pictures, movies, files, etc. You don't need to access that data at the moment but you also don't want to erase it. Can you use the hard drive for your computation, possibly altering its contents temporarily, guaranteeing that when the computation is completed, the hard drive is back in its original state with all the data intact? Intuition tells us that the additional hard drive is not very useful since its contents must be present in some way at every step of the computation and if these contents are incompressible, effectively no extra space is available. Surprisingly it appears that one can make good use of this additional full hard drive. We show that with logarithmic amount of clean space and polynomial full space one can compute the determinant of a matrix, which is believed to be impossible with just logarithmic memory. The full power of such computations is a tantalizing open problem."

J. Ghaderi, S.C. Borst and P.A. Whiting:

**QUEUE-BASED RANDOM-ACCESS ALGORITHMS: FLUID LIMITS AND STABILITY ISSUES.**

**STOCHASTIC SYSTEMS 4 (1), 81-156 (2014).**

Random-access algorithms provide a popular mechanism for sharing the transmission medium among competing users in large-scale wireless networks. In particular, queue-based random-access algorithms are inherently distributed in nature, yet provide the capability to match the optimal throughput performance of centralized scheduling mechanisms. Unfortunately, the specific schemes for which throughput optimality has been established may result in excessive queue lengths and delays. The use of more aggressive access schemes can potentially improve the delay performance but does not offer any universal maximum-stability guarantees. In order to investigate the (in) stability properties of more aggressive schemes, we examined fluid limits where the dynamics are scaled in space and time. In some situations, the fluid limits have smooth deterministic features and maximum stability is maintained. In other scenarios they exhibit random oscillatory characteristics, and instability may occur in some network topologies. In order to reveal these properties we conducted a detailed analysis for a specific topology, and developed a novel approach based on stopping time sequences to deal with the switching probabilities governing the sample paths of the fluid limit process.

# ORGANIZATIONAL ASPECTS

As mentioned, in the first year of NETWORKS, a substantial amount of attention has been paid to setting up the organizational infrastructure, consisting of a Supervisory Board, Management Team, Project Team, members and affiliated members.

The Supervisory Board is formed by the Deans of all the participating Faculties plus the Director of the CWI centre: prof.dr. Karen Maex (UvA), prof.dr. Emile Aarts (TU/e), prof.dr. Geert de Snoo (UL), prof.dr. Jos Baeten (CWI, chair).

The Management Team (MT) consists of the 6 main applicants: Michel Mandjes (programme leader, chair), Mark de Berg, Sem Borst, Remco van der Hofstad, Frank den Hollander, and Lex Schrijver. The MT meets roughly once every 6 weeks to discuss the progress of NETWORKS as a whole, reporting on an annual basis to the Supervisory Board.

The Project Team (PT) is formed by the 11 applicants of the programme (besides the MT, this includes Onno Boxma, Harry Buhrman, Ton Koonen, Johan van Leeuwen, and Gerhard Woeginger). The PT meets on an irregular basis, mainly to discuss aspects concerning the scientific progress of the programme.

Members are staff, postdocs and PhD students paid from the NETWORKS grant or funded from the partners' matching resources.

Affiliated members are not paid by either of these two resources, but are strongly connected to the NETWORKS programme, for instance by playing a co-supervisory role in NETWORKS projects. Affiliated members are invited to all NETWORKS related activities.

By the end of 2014, NETWORKS counted 32 members and 24 affiliated members.

NETWORKS members and affiliated members meet each other three times a year during the so-called "NETWORKS-days". These days typically start by a presentation of the programme leader, highlighting the general progress of the programme. Next, scientific presentations are given by NETWORKS members; in particular, the new hires get the chance to introduce themselves. The day ends with a social event in order to build up and strengthen the NETWORKS community.

In 2014 three such meetings were organized:

- Meeting with the PT, March 26th and April 1st. These meetings were meant to define the scope of PhD and postdoc projects, in such a way to maximally reflect the NETWORKS ambitions. Location: Kaap Doorn, Doorn.
- Meeting with all NETWORKS members, October 17th. General set-up of the programme: scientific presentations of new staff, presentation of "my favorite network problem" by the newly hired PhD students, pub quiz. Location: Grootte Industrieele Club, Amsterdam.
- Meeting with the PT and Tenure Trackers, November 21st. These meetings were meant to discuss the plans for the portfolios Education, Outreach, Valorization and Workshops. Location: Gele Kegels, Eindhoven.

In Spring 2014 a joint application procedure was organized in order to systematically match strong candidates to the NETWORKS vacancies. To facilitate the procedure, a temporary website was developed containing the basic information of the programme as well as the necessary background on the application procedures. Supported by advertisements, a total of 297 applications were received. On June 16th and June 18th 52 interviews took place, either in person or through Skype. Out of these 52 interviews, 18 candidates were selected for a second

interview at the host institution. After this procedure, 10 candidates accepted a position within NETWORKS.

The website used for this application round has been set up, and linked to the already existing NETWORKS website, by “De Zagerij” (graphic design) and “Greenlights Solutions” (web development). A new website is launched early 2015.

During 2014 the support tasks of NETWORKS have been organized in the “NETWORKS Office”. The office consists of Marieke Kranenburg (UvA, general manager), Patty Koorn (TU/e, workshop organization), Petra Rozema (TU/e, education weeks, general support), Monique Onderwater (UvA, webmaster), and Sanne Veenenbos (UvA, financial support). The members of the office are in frequent contact and formally meet three times a year during the NETWORKS-days. In 2015 the NETWORKS Office will be expanded with an outreach staff member and a scientific programmer.

Next to these activities, a consortium agreement was developed, addressing all legal issues associated with the NETWORKS programme. In addition, progress was made related to the financial aspects of the project (budget and administration). To settle these issues, meetings were organized with the legal experts and financial controllers of the partners. NETWORKS submitted the final budget planning to NWO early March 2014. The consortium agreement will be finalized in 2015.

## GRANTS AND AWARDS

### GRANTS

#### NWO VENI Grant

Bart Jansen  
Computer, look before you leap

#### TKI Logistics / NWO

UT main applicant, co-applicants Onno Boxma and Sindo Nunez Queija  
Dynafloat: Managing urban traffic flows dynamically -- the use of floating car data

#### NWO TOP Grant

Remco van der Hofstad, Johan van Leeuwen  
Information diffusion on random graphs

#### TKI Wind op Zee

Co-applicant Stella Kapodistria  
DAISY4Offshore (Dynamic Asset Information System)

#### NWO Mathematics of Planet Earth

CWI main applicant, co-applicant Michel Mandjes  
Rare Event Simulation for Climate Extremes

### AWARDS

Onno Boxma received the 2014 Arne Jensen Lifetime Award at ITC26 (Karlskrona, September 9–11, 2014), “for his outstanding contribution to teletraffic science”.

## NETWORKS MEMBERS

| NAME                           | AFFILIATION | FUNCTION      | NAME                           | AFFILIATION | FUNCTION      |
|--------------------------------|-------------|---------------|--------------------------------|-------------|---------------|
| Abhishek MSc                   | UvA         | PhD – student | Patty Koorn                    | TU/e        | Support staff |
| Murtaza Ali Abidini MSc        | TU/e        | PhD – student | dr.ing. Marieke Kranenburg     | UvA         | Support staff |
| dr. Luca Avena                 | UL          | TT            | dr. Haralambie Leahu           | UvA         | postdoc       |
| Prof.dr. Nikhil Bansal*        | TU/e        | Staff         | prof.dr. Johan van Leeuwen     | TU/e        | Staff         |
| prof.dr. Mark de Berg          | TU/e        | Staff         | prof.dr. Michel Mandjes        | UvA         | Staff         |
| Prof.dr. Hans Bodlaender*      | TU/e, UU    | Staff         | Aleksandar Markovic MSc        | TU/e        | PhD – student |
| prof.dr.ir. Sem Borst          | TU/e        | Staff         | prof.dr. Sindo Nunez Queija*   | UvA         | Staff         |
| prof.dr.ir. Onno Boxma         | TU/e        | Staff         | Monique Onderwater             | UvA         | Support staff |
| prof.dr. Harry Buhrman         | CWI / UvA   | Staff         | Bart Post MSc*                 | TU/e        | PhD – student |
| Souvik Dhara MSc               | TU/e        | PhD – student | Andrea Roccaverde MSc*         | UL          | PhD – student |
| Lorenzo Federico MSc           | TU/e        | PhD – student | Petra Rozema                   | TU/e        | Support staff |
| prof.dr. Remco van der Hofstad | TU/e        | Staff         | prof.dr. Lex Schrijver         | CWI / UvA   | Staff         |
| prof.dr. Frank den Hollander   | UL          | Staff         | dr. Sanchayan Sen              | TU/e        | postdoc       |
| dr. Bart Jansen                | TU/e        | TT            | Nicos Starreveld MSc           | UvA         | PhD – student |
| dr. Oliver Jovanovski          | UL          | postdoc       | Drs. Sanne Veenenbos           | UvA         | Support staff |
| dr. Stella Kapodistria         | TU/e        | TT            | prof.dr.ing. Gerhard Woeginger | TU/e        | Staff         |
| prof.ir. Ton Koonen            | TU/e        | Staff         |                                |             |               |

\* Funded from partners matching resources

## AFFILIATED MEMBERS

| NAME                       | AFFILIATION | FUNCTION | NAME                       | AFFILIATION | FUNCTION      |
|----------------------------|-------------|----------|----------------------------|-------------|---------------|
| prof.dr. Ivo Adan          | TU/e        | Staff    | dr. Julia Komjathy         | TU/e        | Staff         |
| dr. Rene Bekker            | VU          | Staff    | prof. Monique Laurent      | CWI         | Staff         |
| dr. Sandjai Bhulai         | VU          | Staff    | Debankur Mukherjee MSc     | TU/e        | PhD – student |
| dr.ir. Marko Boon          | TU/e        | Staff    | dr. Francesca Nardi        | TU/e        | Staff         |
| dr. Daniel Dadush          | CWI         | Staff    | dr. Jacques Resing         | TU/e        | Staff         |
| prof.dr. Roberto Fernandez | UU          | Staff    | prof.dr. Guido Schaefer    | CWI         | Staff         |
| dr. Diego Garlaschelli     | UL          | Staff    | prof.dr. Bettina Speckmann | TU/e        | Staff         |
| dr. Dion Gijswijt          | CWI         | Staff    | dr. Floske Spijksma        | UL          | Staff         |
| prof.dr. Mathisca de Gunst | VU          | Staff    | prof.dr. Evgeni Verbitskiy | UL          | Staff         |
| dr. Markus Heydenreich     | UL / CWI    | Staff    | dr. Maria Vlasidou         | TU/e        | Staff         |
| dr. Wouter Kager           | VU          | Staff    | dr. Neil Walton            | UvA         | Staff         |
| dr. Bartek Knapik          | VU          | Staff    | prof.dr. Bert Zwart        | CWI         | Staff         |



# PUBLICATIONS



## SELECTION OF RECENT PUBLICATIONS

*Below a selection of recent publications is given. For the complete list, see <http://www.thenetworkcenter.nl/Output/>*

**Hans L. Bodlaender, Bart M.P. Jansen,**  
Stefan Kratsch:

Kernelization Lower Bounds by  
Cross-Composition.

SIAM J. Discrete Math. 28(1): 277-305  
(2014)

J. Ghaderi, **S.C. Borst** and P.A. Whiting:  
Queue-based random-access algorithms:  
fluid limits and stability issues.

Stochastic Systems 4 (1), 81-156 (2014).

**O.J. Boxma** and H. Daduna:  
The cyclic queue and the tandem queue.  
Queueing Systems 77 (2014), 275-295.

**Harry Buhrman,** Richard Cleve, Michal  
Koucký, Bruno Loff, Florian Speelman:  
Computing with a full memory: catalytic  
space.

STOC 2014: 857-866

L. Albertazzi, D. van der Zwaag, C.M.A.  
Leenders, R. Fitzner, **R.W. van der Hofstad**  
and E.W. Meijer:  
Probing exchange pathways in one-dimen-  
sional aggregates with super-resolution  
microscopy.

Science 344(6183): 491-495, (2014).

A. Greven, **F. den Hollander,** S. Kliem and  
A. Klimovsky:  
Renormalisation of hierarchically interacting  
Cannings processes.

ALEA, Latin American Journal of Probability  
and Mathematical Statistics 11 (2014) 43-  
140.

R.G.H. van Uden, R. Amezcua Correa,  
E. Antonio Lopez, F. M. Huijskens, C. Xia,  
G. Li, A. Schülzgen, H. de Waardt,

**A.M.J. Koonen** and C.M. Okonkwo:

“Ultra-high-density spatial division multi-  
plexing with a few-mode multicore fibre”

Nature Photonics, Vol 8 (2014), pp865-870

P.M. van de Ven, A.J.E.M Janssen and  
**J.S.H. van Leeuwen:**

Balancing exposed and hidden nodes in  
linear wireless networks.

IEEE/ACM Transactions on Networking,  
22(5), 1429-1443 (2014)

M. Arendarczyk, K. Debicki and

**M. Mandjes:**

On the tail asymptotics of the area swept  
under the Brownian storage graph.

Bernoulli, Vol. 20, pp. 395-415 (2014).

Tomas Jelinek, Marcus Klaas de Vries and  
**Guido Schäfer:**

Computing optimal tolls with arc restrictions  
and heterogeneous players,

31st International Symposium on Theoretical  
Aspects of Computer Science, 433-444,  
LIPIcs. Leibniz Int. Proc. Inform., 25, Schloss  
Dagstuhl. Leibniz-Zent. Inform., Wadern,  
2014.

Andrea Lodi, Ted K. Ralphs,

**Gerhard J. Woeginger:**

Bilevel programming and the separation  
problem.

Mathematical Programming 146, (2014), pp  
437-458

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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



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