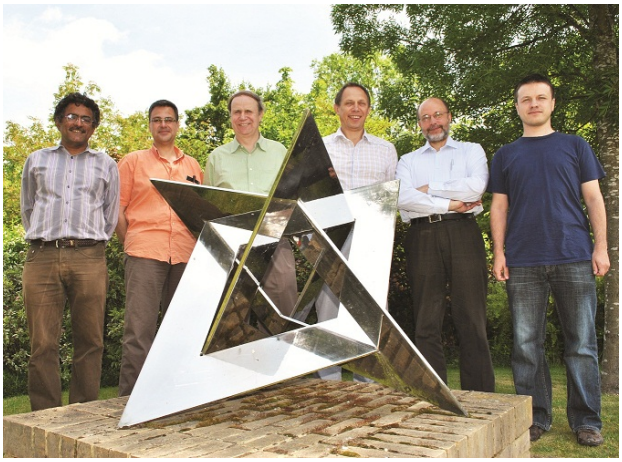
Stochastic Processes in Communication Sciences

11 January to 2 July 2010

Report from the organisers of the programme and of the energy week:
V Anantharam (Berkeley), F Baccelli (INRIA/ENS), D Denisov (Cardiff), S Foss (Heriot-Watt/Novosibirsk), PW Glynn (Stanford), T Konstantopoulos (Heriot-Watt/Uppsala), and S Zachary (Heriot-Watt)



Left to right: V. Anantharam, T. Konstantopoulos, P. Glynn, S. Foss, F. Baccelli, D. Denisov

1 *Scientific background*

The connection between probability (stochastic processes) and communications (networks, information theory) occurred almost simultaneously with the discovery of the telephone. As soon as a system becomes large or complex, probability theory seems to be the right tool to describe its behaviour and help its design. We live in the information era where progresses in communication sciences (wireless communications, Internet) take place at a very high rate. This impacts all aspects of society, from science to economy and political planning.

This programme aimed at the exposition of the latest developments in mathematical sciences lying on the boundary between the disciplines of stochastics and communications. It brought together experts in the fields of probability and communications in order to review and further develop knowledge and trends. Probability theory and communications have developed hand in hand for about a century. The research challenges in the latter field (from telephone networks to wireless communications and the Internet) have spurred the development of the mathematical theory of stochastic processes, particularly in the theory of Markov processes, point processes, stochastic networks, stochastic geometry, stochastic calculus, information theory, and ergodic theory to name but a few. Conversely, a large number of applications in communications would not have been possible without the development of stochastics.

The programme was attended by 87 long-term participants and 23 short-stay ones, several of which were young researchers or graduate students. It also hosted several workshops and special events, with many more participants, in the following areas:

An inaugural workshop on the interface between Probability and Communications which explored probabilistic methods (e.g. Information Theory) for communication systems.

A workshop on stochastic networks which was planned to cover traditional and new aspects of the field, ranging from performance analysis of queueing and communication networks to new applications in biological and chemical networks.

A workshop on spatial networks which presented methods based on stochastic geometry, random graphs, percolation, and random matrix theory, with particular emphasis on applications to wireless networks.

A workshop on simulation of networks, focusing on the stochastic simulation of complex networks via Monte Carlo and newer approaches, such as particle methods.

A workshop on the statistics of networks the intention of which was to understand data collection and analysis in networks and their further use in building mathematical models.

Two special events were also organised: The first one was a one-day open for business event on communication architecture for the future. The second one was the energy systems week, a special programme organised around the new relations between networks and power systems.

Special emphasis was placed on young researchers and students throughout the programme. This was culminated with the satellite workshop for young researchers which took place in Edinburgh.

2 *Structure of the Programme*

The programme ran over five and a half months. Several talks were organised on a regular basis, the majority of which were given at the Newton Institute, as part of the programme, video-taped, and now available on the Newton Institute webpage. Several participants also gave invited seminar talks at Cambridge, Glasgow, Imperial College, Leeds, Leicester, Loughborough, Oxford, Queen Mary, UCL, Edinburgh, Paris, Cardiff, Liverpool.

Inaugural Workshop on "New Topics at the Interface Between Probability and Communications"

The aim was to bring together several leading experts to deliver overview lectures surveying the range of problems in the modern communication sciences that are studied using stochastic techniques, and to provide their individual perspectives on what are the important directions to develop this interaction over the coming years. The interplay between these fields has been enormously fruitful over the last couple of decades, with stochastic techniques making an impact on the development of communication systems and problems in communications leading to new developments in the theory of stochastic processes.

A number of outstanding lectures were delivered during this workshop, most of which are available for viewing in their entirety in video format on the web site of the institute. The topics that were surveyed ran from limit theorems for stochastic networks (K. Ramanan), scheduling, load balancing, and congestion control (A. Ganesh, J. Tsitsiklis, J. Walrand, D. Wischik), rate and delay guarantees in wireless networks (P. Kumar, M. Medard, D. Tse), aspects of heavy-tailed and long-range-dependent behavior in networks (B. Prabhakar, S. Resnick), and the role of iterative algorithms (L. Massoulie, A. Montanari) and novel estimation techniques for large scale problems (A. Orlitsky). A refereed poster session as well as two very lively open problem sessions rounded out the workshop. The open problem sessions provoked substantial discussion and at least one of them was solved during the course of the program.

Details are at `http://www.newton.ac.uk/programmes/SCS/scsw01.html`

Stochastic Networks Workshop

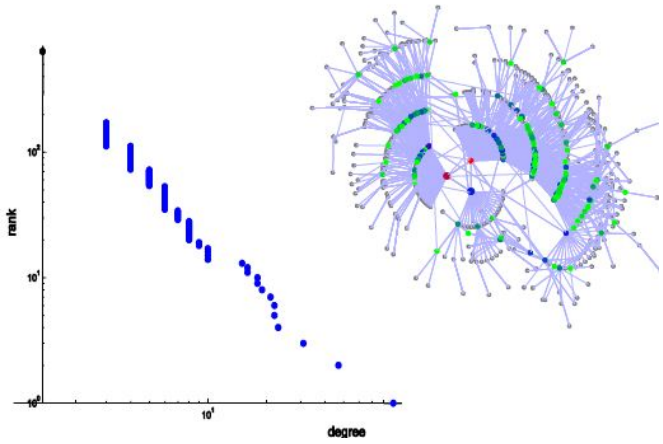
Stochastic networks is a multifaceted area of research dealing with the stability, control, performance, approximation and design of stochastic models of networks. It gives rise to challenging

and subtle mathematical problems, whose solution often requires a combination of ideas and techniques from several branches of mathematics, including probability theory, stochastic processes, analysis, optimization, combinatorics and graph theory. Research in this area is strongly motivated by applications in diverse areas, ranging from the traditional areas of telecommunications and manufacturing to service operations, biological and social networks and revenue management. The aim of this workshop was to bring together experts in this area to survey recent developments and identify future research directions. The workshop has been structured so as to maximize interactions between speakers and participants and to facilitate a fruitful exchange of ideas. The tradition on Stochastic Networks workshop was started in 1987 and that has now become a bi-annual event.

The workshop hosted a number of high-quality lectures by experts in the field, young researchers but also people in related areas. The workshop was opened by a lecture of François Baccelli on information theoretic aspects of point processes. Marty Reiman, Bert Zwart, Srikant, Carl Graham, and Philippe Robert gave talks on various aspects of queueing networks (inventory systems, scheduling, congestion control, numerical methods, and stabilty). Pablo Ferrari spoke about a traffic model that leads to coalescing Brownian motions. Bruce Hajek delivered the Rothschild visiting professor lecture on mathematical models of peer-to-peer communication networks. Venkat Anantharam talked about the impossibility of getting rid of long-range dependence by data compression. David Anderson spoke about chemical reaction networks and exhibited simulation techniques (of stochastic differential equations) which could be useful in other types of networks as well. Ruth Williams gave a talk on an application of queueing methods to enzymatic networks, which was based on her collaboration with biologists. Sebastien Roch overviewed probabilistic techniques in phylogenetic networks. Steve Evans also spoke about networks arising in biology. Marc Lelarge gave a talk on matchings of random graphs. Maury Bramson gave an impressive lecture on a truly exceptional result exhibiting a 6-dimensional reflecting Brownian motion which is one hand positive recurrent but, on the other hand, its fluid limit is divergent. The workshop closed with a short overview lecture of Frank Kelly, one of the founders of the field.

It became clear that the scope of Stochastic Networks, as a discipline, goes beyond some traditional queueing-theoretic applications and that it embraces a number of several areas of Applied Probability. Conversely, methods developed for Stochastic Networks have found applications in other areas.

Details are at`http://www.newton.ac.uk/programmes/SCS/scsw02.html`



Spatial Network Models for Wireless Communications

The workshop gathered 86 attendees from all over the world. It consisted of 16 lectures and a poster session with a dozen posters or so. It received additional support by the National Science Foundation of the USA and by the EuroNF Network of excellence of the European union.

Two communities met, we think, for the first time: on one side, specialists of random graphs and stochastic geometry interested in networks, which highlight lectures like those of D. Aldous, B. Bollobas, C. Bordenave, G. Last, M. Penrose, Y. Peres or R. Van der Hofstad; on the other side, specialists of wireless networks interested in the development of modeling tools involving spatial components, with highlight lectures like those of B. Blaszczyszyn, M. Franceschetti, P. Gupta, O. Leveque, D. Shah, E. Soljanin, P. Thiran, L. Xie or S. Zuyev. Several common grounds between these two communities became evident from the lectures, in particular the central role played by phase transitions arising in percolation for analyzing connectivity in large networks.

The main outcomes of the workshop were: 1) the connections that were made between the geometry of a network and the quality and quantity of information transmission in this network; 2) the methodological advances based on network information theory and spatial stochastic networks to analyze this; 3) the identification of several classes of new mathematical problems stemming from wireless network design.

Several new collaborations on these topics which started at the occasion of the workshop are listed in the individual reports.

Details are at `http://www.newton.ac.uk/programmes/SCS/scsw03.html`

Satellite Workshop on Stochastic Processes in Communication Sciences for Young Researchers

This was a satellite workshop, held at the International Centre for Mathematical Sciences in Edinburgh, organised by D. Denisov, M. Lelarge and B. Zwart. It was supported by INI and by the Network of Excellence Euro-NF. The meeting was aimed at the young researchers in the area of Stochastic Processes in Communications Sciences. It attracted also an interest from more experienced researchers as well. There were about 60 participants.

The workshop included both research talks and more elementary tutorials. There were five tutorial session given by the leading experts in the area: Bartek Blaszczyszyn, Philippe Robert, Remco van der Hofstad, Martin Wainwright and Damon Wischik. Each tutorial consisted of 3 lectures in order to give a broader overview of a certain direction of research. As was evidenced by feedback forms the tutorials were highly regarded by the audience. They covered the following subjects: stochastic geometry and wireless networks, probabilistic methods in the analysis of stochastic networks, processes on random graphs, graphical models and message-passing algorithms, queueing theory for switched networks.

Apart from the tutorials a number of research talks were given to cover recent developments in the area and presented new challenges. The talks were given by well established researchers: Sem Borst, Jose Blanchet, Peter Glynn, Thomas Kurtz, Andrea Montanari, Alexandre Proutiere, Amin Saberi and Leandros Tassiulas. In particular the the following themes were considered : (a) message passing algorithms; (b) social networks ; (c) wireless networks ; (d) importance sampling; (e) stability for networks. Importantly, this workshop also gave an opportunity for younger researchers to present their results to a broader audience. This resulted in a number of interesting talks and a poster session.

Details are at `http://www.icms.org.uk/workshops/stocpro`

Energy Systems Week Workshop

This workshop focused on mathematical and statistical challenges in the design and management of future energy systems, notably those in networks for the supply and distribution of electrical energy.

Adaptation to new, non-fossil-fuel, sources of energy poses many interesting mathematical challenges in the generation and distribution of electrical power. Notably, renewable sources such as wind power produce supplies which are highly variable and often unpredictable even on relatively short timescales. Further, new sources of generation capacity, whether renewable or nuclear, are often located far from the urban and industrial areas they must serve. Thus in the future there will be a need to manage a complex and stochastic system, in which supply and demand need to be managed on a minute-by-minute basis, and in which there are many competing operators each seeking to maximise their own returns.

The first two days of the workshop consisted of tutorials by energy systems experts on the mathematical challenges now posed: Ben Hobbs (Johns Hopkins), Danny Ralph (Cambridge) and Seyn Meyn (Urbana-Champaign) addressed issues in the dynamical management of multivariate-player systems; Glenn Vinnecombe (Cambridge), Janusz Bialek (Durham) and Daniel Kirschen (Manchester) spoke about the stability and optimal control of power networks; Mark O'Malley (Dublin) introduced the statistical and optimization problems in the integration of wind energy into electricity networks. These sessions were all extremely lively and provoked both extensive and intensive exchanges between the mathematicians, economists and power systems engineers attending the workshop.

The third day of the workshop featured presentations on high-level strategy and policy issues for future energy systems: Seyn Meyn spoke on the need for regulation in energy markets; Steve Smith (Ofgem) spoke on ensuring the adequacy of future energy systems, and Janusz Bialek on their mathematical modelling; Chris Murray (National Grid) discussed the role of National Grid in balancing future energy security, sustainability and affordability. These presentations were followed by a lively panel discussion in which mathematicians and economists strove hard to understand each other's viewpoints.

The final day focused on some specific problems and challenges. Samantha Riches (EPSRC) introduced the UK Research Councils Energy Programme; Andrew Richards (National Grid) discussed statistical issues in demand forecasting; Nafees Meah (Dept of Energy and Climate Change) spoke about the problem of how to effectively incorporate uncertainty in economic projection models so as to properly inform policy makers; Mark Tritschler (KEMA consulting) presented mathematical challenges in the control of smart grids.

The workshop proved a highly effective base for identifying these many important research issues and planning how best academics and industrialists with many different areas of expertise should work together to address them.

Details are at `http://www.newton.ac.uk/programmes/SCS/esw.html`

Simulation Workshop

Stochastic simulation plays an important role in the analysis of networks in general. A significant portion of the simulation activity concentrated on the design and analysis of Monte Carlo methods for rare events a topic that is known to be both challenging and important within applied probability at large. A number of significant contributions were discussed in the workshop, including new insights into the understanding of particle methods for rare events, optimally designed algorithms for a large class of stochastic networks, and asymptotically optimal algorithms for many server systems. Nevertheless, important open problems remain in the field, most notably

the development of tractable and implementable rare event methods for non-Markovian stochastic networks. The workshop was organized jointly with RESIM, which is an international workshop on rare event simulation that occurs every two years and has a very strong international representation. The structure of the workshop was designed in order to transition smoothly to the statistics component. In particular, after two days held jointly with RESIM, topics at the interface of statistics and simulation, such as Markov chain Monte Carlo methodology for networks, were discussed. A special issue of invited keynote papers to be published by QUESTA, a leading Springer sponsored journal in stochastic operations research, is planned.

Details are at `http://www.newton.ac.uk/programmes/SCS/scsw05.html`

Statistics of Networks Workshop

Networked systems are generating ever-richer sets of data across many engineering, economic, biological and social science disciplines. The intention of this workshop was to bring together leading data-oriented researchers in the many disciplines that are now utilizing network models in the study of fundamental questions arising in their fields. Network models have become a fundamental tool in understanding and predicting phenomena in areas as disparate as biology, finance (default contagion models) and the evolution of human social communities. In view of the fact that network models have long played a central role in the design and control of communications systems, the workshop presented an opportunity to identify synergies between the research thrusts being pursued by the various communities involved in the analysis of network data. Specific areas addressed by the workshop included statistical analysis of network traffic (including inference in the presence of missing data), detection of network intrusion and congestion, determination of community structure, use of multiscale methods, and development of graphical modeling and inference tools.

Details are at `http://www.newton.ac.uk/programmes/SCS/scsw08.html`

Communication Architecture for the Future. Low Cost and Resilience in the Face of Uncertainty

This half-day workshop was supported also by the Higher Education Innovation Fund (HEIF4) of the University of Cambridge. It brought together experts in UK wireless spectrum auctions (such as Graham Louth of Of Com) with researcher in auction theory. It was a great opportunity to compare theory and practice, and discuss future directions.

See `http://www.newton.ac.uk/programmes/SCS/caf.htm` for the programme and related info.

3 *Outcomes, achievements, and conclusions*

The programme attracted a large number of participants, experts and young researchers alike. The brilliant idea of the Newton Institute to run in parallel two programmes on different aspects of probability (out programme and that on stochastic partial differential equations) resulted in a great synergistic atmosphere with participants of one programme interacting and attending talks of the other. It is a common acknowledgment that several of us gained a lot from this.

From the participants' comments it became clear that there was a consensus about the outstanding level of many lectures. Several people found the tutorials and keynote talks very beneficial. Everybody found the diversity offered by the programme, and the mix between theory and applications well-planned and offering new perspectives.

We are very pleased that original intention, to emphasise the interplay between theory and applications, and between communications and probability, was achieved. In the words of Tom Kurtz,

"The subject [of communications and networks] has driven the development of mathematics both historically and in recent years. Much of the development of our understanding of constrained Markov processes that has occured over the last 20 years has been motivated by problems arising in communications." He also added that "Modelling wireless networks has motivated developments in graph theory. Network problems have stimulated a lot of the recent work on ergodicity of Markov processes. Conversely, mathematical models are used in designing communication systems."

Many important collaborations were started or developed during the programme. Examples include: collaboration between H Thorisson, G Last and P Mörters on random time shifts and two-sided Brownian motion; between I Ziedins, T Kurtz and M Reiman on diffusion approximation for loss networks; a new line of research started by F Baccelli, A Rybko and A Vladimirov on phase transitions for queueing dynamics of wireless networks; new collaborations between T Konstantoloulos and V Anantharam on the integral representation of Skorokhod reflection; between A Rybko, S Zuyev and Y Sinai on a class of Markov processes; between K Debicki and M Mandjes on asymptotics of the supremum of a Gaussian queue; between J Martin and S Foss on the last passage percolation; between M Zazanis and T Konstantopoulos on iterates of Bernstein operators; between I Norros, D Denisov and N Leonenko on multifractals; between J Cruise, D Wischik and D Shah on scheduling problems, between M Mandjes and P Glynn on workload autocorrelation of queues fed by long-range dependent inputs. The list is far from exhaustive. Many papers and several books have been completed during the programme. Several papers have appeared as the Newton Institute preprint series and some will appear soon. A running list of publications with acknowledgements to the SCS programme and of working papers may be found at `http://www.ma.hw.ac.uk/~foss/SCSpublications/`

As organisers, we are particularly indebted to the Newton Insitute for the hospitality, for providing the excellent working atmosphere, for the high-quality video-taping of the lectures, and for giving us the opportunity to develop research collaborations. It was pleasing to witness a wide array of mathematical fields in interaction with communications. We expect that the programme will have a lasting impact to the work of all the participants and those who devote the time to, for instance, watch the recorded lectures. For us, the programme did not end in the summer of 2010. Rather, it is a common feeling that it was the beginning of a new era. We expect that it will lead to other meetings in the coming years, meetings involving mathematicians and practitioners, as well as the further development of new kind of mathematics.