Report for
Dagstuhl Seminar 00151

Advanced Stochastic Modelling in Telecommunications

April 10th to 14th, 2000

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Contents

Introduction

Telecommunication systems have a long tradition as a source and inspiration for stochastic models which are used at every stage, from conception to planning, realization and operation. Hot topics at the present time concern mobile telecommunications and developments in internet-based services andsystems.

Internet-based services have created an enormous interest when they were first proposed, and are still the subject of intense scientific activity. During the workshop which was held this year, we have had several presentations in that area, and it is clear that the subject is not closed.

Mobile telecommunications are still in full development, both technological and methodological. No week goes by without a new announcement for an international conference devoted to the subject. This is spurred by the adoption of cellular telephones by users throughout the world, the deployment of IRIDIUM and future low earth orbit satellite systems, and the integration of fixed networks with wireless systems. These developments, in turn, create more research on mathematical models of spatial traffic, etc.

The strength of the seminar resided in the mix of participants: a sizeable proportion are employed in industrial research centers, and, among those from the academic world, several have close working relationship with industry. This lead to extremely interesting interactions among the participants, a varied set of points of views and a rich collection of problems addressed and models analyzed.

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Time Schedule

Monday, April 10th

9.00 – 10.30	Fluid Flow Models	Markus Fiedler	New Applications for the Stochastic Fluid Flow Model in Networking
	TCP Systems	Matthew Roughan	TCP Dynamics - Self-Organising Criticality and the Internet
Coffee Break			
10.45 – 12.15	Traffic Characteristics	Ake Arvidson	Some Results on TCP Traffic Models
		Joachim Charzinski	Internet Access Traffic Characteristics
Lunch			
14.00 – 15.30	Traffic Modelling	Ake Arvidson, Joachim Charzinski, Matthew Roughan	Panel Discussion
Coffee Break			

Tuesday, April 11th

9.00 – 10.30	Optimization	Rudolf Mathar	On the Optimal Base Station Density for CDMA
		Stefan Köhler	Towards an Optimization of the Routing Parameters
Coffee Break			
10.45 – 12.15	Network Planning	Lothar Breuer	A Planning Tool for Mobile Communication Networks
	Estimation	Bo Friis Nielsen	Estimation of MAP-Parameters from Counts
Lunch			
14.00 – 15.30	Modelling	Ulrich Herzog	Insularity of Performance Evaluation? Profit from an Integrated Approach
		Holger Hermanns	Model Checking Continuous Time Markov Chains
Coffee Break			
16.00 – 17.30	IP and Network Planning	Bo Friis Nielsen, Stefan Köhler, Udo Krieger	Panel Discussion

Wednesday, April 12th

9.00 – 10.30	Analysis of Stochastic Models	Reinhard German	New Embedding Schemes for Non-Markovian Models
		Markus Siegle	Multi-Terminal Binary Decision Diagrams to Represent and Analyse Continuous Time Markov Chains
Coffee Break			
10.45 – 12.15	Wireless Networks	Armin Heindl	Performance Evaluation of Wireless LANs with Stochastic Petri Nets
		Michael Menth	A Numerical Framework for Solving Discrete and Finite Markov Models – Applied to Multiplexing Voice over IP-Networks
Lunch			
Social Event: Excursion to Idar-Oberstein			

Thursday, April 13th

9.00 – 10.30	Spatial Models for CDMA	Dieter Baum	Models for CMDA-based Cell Networks: Multi-Server Stations with Spatial Markov Additive Processes of Arrivals and Finite Capacity
		Stephen Hanly	Multi-User CDMA Receivers with Spatial Diversity
Coffee Break			
10.45 – 12.15	Low Orbit Satellites	Nikhil Jain	Management of Grade of Service in Leo Satellites
		Marie-Ange Remiche	On the Exact Cumulated Interference Power at Leo Satellite According to Earth Stations Location
Lunch			
14.00 – 15.30	QDB Models	Peter Taylor	Quasi-Birth-and-Death-Models with Heavy-Tailed Queue
		Guy Latouche	The Condition Number of the Caudal Characteristic as an Indicator of the Dynamic Behavior of a QBD
Coffee Break			
16.00 – 17.30	Wireless Systems	Stephen Hanly, Nikhil Jain, Rudolf Mathar	Panel Discussion

Friday, April 14th

9.00 – 10.30	Heavy-Tailed Models	Sem Borst	Reduced-Load Equivalence and Induced Burstiness in Generalized Processor Sharing Queues with Long-Tailed Traffic Flows
		Jacques Resing	Polling Systems with Heavy-Tailed Service and/or Switchover Times
Coffee Break			
10.45 – 12.15	Concluding Session	Guy Latouche, Phouc Tran-Gia	
Lunch			

Summaries of given Talks

New Applications for the Stochastic Fluid Flow Model in Networking

Markus Fiedler, University of Karlskrona/Ronneby

The talk addresses some new applications for the fluid flow model that underline the versatility of this model for performance evaluation both within and at the edge of wired and wireless networks. Crucial properties of the model that provide the basis for this versatility are presented, e.g. the equivalence of sources and servers. Open issues that come along with these applications are also identified and might serve as a basis for discussion.

TCP Dynamics (Self-Organising Criticality and the Internet)

Matthew Roughan, University of Melbourne

TCP/IP (the Transmission Control Protocol/Internet Protocol) is the basis of the Internet. Included in TCP is a window flow control designed (by Van Jacobson) to prevent congestion collapses such as that which crippled the Internet in October 1986. Recently several people have started studying the TCP congestion controls in order to understand the performance of TCP/IP networks. Many simple models have been proposed, often assuming that individual TCP sources are only weakly coupled. However, there is good evidence that TCP sources are often quite strongly coupled -- in fact they may become synchronised. Hence there is a need to study the ways in which sources may interact. In our study we show that the interactions between TCP sources may even lead to properties such as Long-Range Dependence (LRD). It is now well known that data traffic exhibits LRD, but the current wisdom is that it arises from heavy-tailed file-size distributions, or inter-activity periods. We deliberately avoid using any such distributions in our study, and therefore our findings seem to indicate that there are other possible sources of LRD in data traffic. Furthermore, we note that different types of scaling behaviour such as Multi-Fractality, which can be observed in Wide-Area Network traffic, can also be generated through the dynamics of the TCP congestion controls. One potential mechanism which might be responsible for the observed LRD is Self-Organising Criticality (SOC). Systems in phase transition, or at a critical point often exhibit heavy-tailed behaviour (for instance consider the M/M/1 queue when the traffic intensity rho=1). SOC is a mechanism whereby a system's dynamics inherently force it into the critical region where heavy-tailed (and hence LRD) behaviour may occur.

New Applications for the Stochastic Fluid Flow Model in Networking

Åke Arvidson, Ericsson Sweden

I intend to present some new simulation results where two approachees to TCP traffic modelling are compared. In one approach, link traffic is modelled and in the other user behaviour and protocols are modelled. The former approach can be referred to as an open loop model in which the congestion control of TCP is disconnected whereas it the latter is a closed loop model with the congestion control activated. We will show that the results you get are very different. The conclusion is that we need to develop closed loop models and we will also present some properties that these models should have. Parts of the talk refer to material that was already presented at the ITC last year, and some parts are new.

Internet Access Traffic Characteristics

Joachim Charzinski, Siemens AG, Munich

Traffic characterisation can be done on different time resolution levels, which describe different properties of user and application behaviour. In addition, the traffic caused by elastic Internet applications is influenced by two major feedback loops: TCP flow control and the feedback from network performance on user behaviour. Currently, most traffic in the Internet backbone and access networks is elastic (WWW, E-Mail, file transfer) traffic. On the basis of long-time traffic traces, characteristics of Internet client traffic are presented for different time scales and flow levels. Investigations of the correlation structure of some flow characteristics reveal that symmetrical connections occur even at high bit rates. A large number of TCP connections can therefore benefit from symmetric access network bandwidths although HTTP, e-mail and file transfer traffic on average is asymmetric.

On the Optimal Base Station Density for CDMA Cellular Networks

Rudolf Mathar, RWTH Aachen

The minimal base station density for a CDMA cellular radio network is determined such that the outage probability does not exceed a certain threshold. Base stations are assumed to be located on a regular triangular grid of a certain distance, while mobiles are randomly distributed according to a two-dimensional Poisson process. Each mobile may be in soft hand-off with at most four surrounding base stations, applying power control to the one with least attenuation. By using normal approximations to the total interference power at a reference base station for a purely deterministic power propagation law and for a correlated log-normal shadowing law the optimum base station distance is shown to be proportional to the inverse of the square root of the traffic intensity.

Towards an Optimization of the Routing Parameters for IP Networks

Stefan Köhler, University of Würzburg

Routing is one of the key issues in IP networks. However, few methods exist to optimize the routing for a particular network. Most effort is invested to improve the routing protocols itself. In this work a possibility to specify appropriate values for the link costs of a given network with linear programs is presented. The obtained link costs can be directly translated into values suitable for the metrics of the two currently most important routing protocols EIGRP and OSPF in today's Internet. With this method a homogeneous distribution of traffic in IP-based networks can be achieved.

A Planning Tool for Mobile Communication Networks

Lothar Breuer, University of Trier

The planning of mobile communication networks requires to have a model of the foreseeable amount of traffic in order to allocate adequate cell capacities. The present paper applies a spatial infinite server queue to answer that question. First, a natural generalization of the BMAP concept is introduced and called Spatial Markovian Arrival Process (SMAP). SMAPs generalize BMAPs towards time--inhomogeneous arrival rates and spatially distributed batch arrivals. Then, spatial infinite server queues with SMAP arrivals and general service time distributions (depending on arrival positions) are examined in several stages of generality, including user movements and periodic arrival intensities. Finally, it is shown how to apply spatial infinite server queues to the planning of mobile communication networks.

Estimation of MAP-Parameters from Counts

Bo Friis Nielsen, Technical University of Denmark

The Markovian arrival process is a very versatile and flexible tool for modelling highly variable traffic in modern communication systems. Usually data on packet traffic is collected on an aggregated basis i.e. as the cumulative number in consecutive time slots rather than the timestamps from individual packets. Work in progress addressing this issue will be discussed. So far, thorough investigations have been performed estimating parameters of the interrupted Poisson process based on absorbed values of the counting process in some fixed time slot.

Insularity of Performance Evaluation? Profit from an Integrated Approach!

Ulrich Herzog, University of Erlangen-Nürnberg

One often complains about the insularity of performance evaluation. But did we learn from Dormenico's analysis? Did we narrow the gap between system designers and pe-specialists? Smoothly enhanced functional description techniques are a significant contribution to reach this goal. Typical examples are stochastic extensions of Petri nets, graph models, process algebras or specification languages such as SDL/MSC and LOTOS. We favor Stochastic Process Algebras and LOTOS because of their unique features allowing one to systematically specify (and model) complex systems from smaller ones: There are mechanisms available for the composition of behaviors as well as for abstraction of internal behavior. In addition, process algebras offer an algebraic characterization of equivalent system behavior. These features are very attractive for the performance comparison of different system designs, for automatic model reduction techniques as well as for hierarchical modelling. We introduce the fundamental ideas and concepts and we value state-of-the-art as well as trends.

Model Checking Continuous Time Markov Chains

Holger Hermanns, University of Twente

Continuous-time Markov chains (CTMCs) are widely used to describe stochastic phenomena in many diverse areas. They are used to estimate performance and reliability characteristics of various nature, for instance to quantify throughputs of manufacturing systems, to locate bottlenecks in communication systems, or to estimate reliability in aerospace systems. CTMCs are the underlying semantic model of major high level performance modelling formalisms such as stochastic Petri nets, stochastic process algebras, and Markovian queueing networks. Model checking is a very successful technique to establish correctness of systems from similar application domains, usually described in terms of a nondeterministic finite-state model. One of the major reasons for the success of model checking tools in practice is the efficient way to cope with the state-space explosion problem, using symbolic (BDD-based) techniques. In this talk, I will discuss the use of symbolic model checking to assess performance and reliability properties of CTMCs. With this approach, properties-of-interest are expressed as formulas of a stochastic extension of the logic CTL and interpreted over CTMCs. Model checking this logic requires the solution of linear systems of equations and of systems of Volterra integral equations. I will outline approximate techniques for solving the equation systems, and present a JAVA implementation of a Markov chain model checker.

New Embedding Schemes for Non-Markovian Models

Reinhard German, Technical University of Berlin

We consider the problem of analysing non-Markovian stochastic models numerically. A well-known approach is to embed a Markov chain at instants of regeneration. It allows us to have models with generally timed activities under the restriction that they are mutually exclusive. In order to deal also with models in which generally timed activities are concurrent, it is possible to use hierarchically structured regeneration intervals. However, in the general case complex expressions are obtained, and the practical relevance may be limited. Going one step back is to have models with concurrent deterministically timed activities which are appropriately synchronised. This leads to a concept of cascaded embedding and to comparatively simple expressions. We will illustrate this concept by modeling a double token bucket with stochastic Petri nets.

Multi-Terminal Binary Decision Diagrams to Represent and Analyse Continuous Time Markov Chains

Markus Siegle, University of Erlangen-Nürnberg

Binary Decision Diagrams (BDDs) have gained high attention in the context of design and verification of digital circuits. They have successfully been employed to encode very large state spaces in an efficient, symbolic way. Multi Terminal BDDs (MTBDDs) are generalisations of BDDs from Boolean values to values of any finite domain, in our case a finite set of transition rates. In this talk, we investigate the applicability of MTBDDs to the symbolic representation of continuous time Markov chains, derived from high-level formalisms such as queueing networks or process algebras. We point out the advantages that can be gained if symbolic representations are constructed in a compositional fashion. Based on MTBDDs, we discuss iterative numerical methods to compute the steady-state probability vector that work in a completely symbolic way. We also give an overview of our prototype tool which implements all aspects of symbolic model construction and analysis.

Performance Evaluation of Wireless LANs with Stochastic Petri Nets

Armin Heindl, Technical University of Berlin

In late 1997, IEEE standardized the physical layers and the medium access for wireless local area networks. This contribution presents a performance study of the distributed coordination function, the fundamental contention based access mechanism. Most performance studies adopt unchecked simplifying assumptions or do not reveal all details of the simulation model. A Stochastic Petri net model is developed, which captures all relevant system aspects in a concise way. Simulation allows to quantify the influence of many mandatory features of the standard on performance, especially the backoff procedure, extended interframe spaces, and the timing synchronisation function. We identify conditions when simplifying assumptions commonly used in analytical modeling are justified. Applying these conditions, we derive a more compact and analytically tractable model from the detailed model.

A Numerical Framework for Solving Discrete and Finite Markov Models – Applied to Multiplexing Voice over IP-Networks

Michael Menth, University of Würzburg

Discrete Markov Models are often the basis for performance evaluation of telecommunication systems. For the description of models the state transition matrix is normally used, which is already a combination of the mere model behavior and the influence of probabilistic events. A new specification clearly separates both aspects. The formal description focuses on the functionality of the model. It consists of renewal points, model states (X), and influencing factors (Y) which are both represented by random variables. The state transition function $Xn+1=f(Xn,Y)$ determines the future model state given the current one and the influencing factor. This functional description facilitates dealing with complex Markov models. A compiler syntactically derives the code for a numerical program that iteratively computes the stationary state distribution without explicitly requiring the state transition matrix. This approach allows the treatment of very large Markov chains even if sparse matrix methods exceed the computer's memory.
We apply this framework to investigate the following system. Compressed voice samples are tunneled over IP networks in the RTP/UDP/IP protocol stack which leads to a very high overhead (200% - 300%). As a consequence, the throughput in terms of transported user data in the network is fairly low. Recently, the IETF suggests to overcome this by carrying several voice samples with the same destination node in one packet. The Real-time Transport Protocol (RTP) is used for multiplexing to share the RTP header information for many voice samples. Collecting voice samples for the common transmission delays them and a timer is used to limit their delay. Leaky bucket spacing is further applied to the outgoing IP traffic. The voice samples have strict requirements for loss and delay that must be met in this scenario. The numerical results we get from this model illustrate that 60% of the bandwidth can be saved by RTP multiplexing and that there is an optimum timer value that maximizes the link utilization while meeting the QoS conditions.

Models for CDMA-based Cell Networks: Multi-Server Stations with Spatial Markov Additive Processes of Arrivals and Finite Capacity

Dieter Baum, University of Trier

The class of level dependent spatial (univariate or multivariate) Markov-additive processes of arrivals (MAPAs), containing the set of spatial BMAPs as a subclass, has been proven to be well suited for modelling the input stream of integrated services data networks. Multi server queues with arrival processes of this type can be used, in particular, to model the behaviour of CDMA based cell networks with non-moving customers. In this paper we recapitulate results for BMAP/G/□ and MAPA/G/K/K stations together with their multidimensional as well as spatial variants. These results are based on the solution of certain matrix differential equations. Additionally, we present a new approach to take into account movements of customers, such that, for example, the transient as well as steady state distributions of the number of moving mobiles with calls in progress can be computed for any subregion within some district of interest.

Multi-User CDMA Receivers with Spatial Diversity

Stephen Hanly, University of Melbourne

In this talk, we examine the capacity of a CDMA link with spatial diversity i.e. where the receiver is equipped with an antenna array. We model the case of independent, identically distributed, flat fading to each antenna. We show that asymptotically, in the limit of large spreading, a resource pooling phenomena occurs: the system behaves like a single antenna, with received power the pooled received power from each antenna of the original system, and processing gain the product of the original processing gain and the number of antennas. The theory of large random matrices and their eigenvalue distributions is used to get a ``law of large numbers'' for the signal to interference ratio, from which the resource pooling phenomena emerges.

Management of Grade of Service in Leo Satellites

Nikhil Jain, Qualcomm Inc., USA

A framework for management of service in satellite systems is needed. This talk attempts to develop one such framework. We describe a model that uses two classes of arrivals with n servers. One of the class of customers have a higher priority than the other class. Some servers are reserved for higher priority customers. The higher priority customers are not queued but are blocked if the server is not available. The queue is infinitely long. The talk outlines a queuing model that gets a closed form solution of the ergodic probabilities of the system. Furthermore, some unique properties of the system are exploited to develop a optimization technique. The combination of the optimization technique and the closed form solution will allow this scheme to be deployed in the communication system where this system gets reprovisioned automatically as the traffic changes.

On the Exact Cumulated Interference Power at a Leo Satellite According to Earth Stations Location

Marie-Ange Remiche, University of Brussels

Due to their algorithmic tractability, Isotropic Phase Planar Point Processes constitute a set of attractive point processes in the plane. In this presentation, a already analysed technique is extended in order to characterize marked IPhP^3, where in this analysis the marks are deterministic fonctionnals of the location itself of the points. Those marked point processes found their interest in wireless model where not only the number of user in a given area matters, but also their associated marks. An application motivates this whole study: how to measure the two first moments of the cumulated interference power at a satellite in a Low Earth Orbital satellites telecommunication system, where CDMA is used.

Quasi-Birth-and-Death-Models with Heavy-Tailed Queue Length Distributions

Peter Taylor, University of Adelaide

It seems to be widely-believed that heavy-tailed behaviour in a queue is incompatible with a Markovian description for the arrival and service processes. In this talk we demonstrate that, provided that the Markovian description of either the arrival or service process is allowed to have infinitely many states, this is not true. We achieve this by exhibiting a class of M/Ph/□ queues which have heavy-tailed queue length distributions.

The Condition Number of the Caudal Characteristic as an Indicator of the Dynamic Behavior of a QBD

Guy Latouche, University of Brussels

The spectral radius ε of the rate matrix of an ergodic QBD is known to be indicative of the tail behavior of the steady state probability distribution. For that reason, ε is called the caudal characteristic and is used as a descriptor of the dynamics of the QBD. In this paper, we show that additional information can be given by the condition number of the spectral radius $\kappa(\varepsilon)$, especially in those cases where $\kappa(\varepsilon)$ is huge.

Reduced-Load Equivalence and Induced Burstiness in Generalized Processor Sharing Queues with Long-Tailed Traffic Flows

Sem Borst, CWI Amsterdam

We discuss the asymptotic behavior of long-tailed traffic flows under the Generalized Processor Sharing (GPS) discipline. GPS-based scheduling algorithms, such as Weighted Fair Queueing, play a major role in achieving differentiated quality-of-service in integrated-services networks. We show a sharp dichotomy in qualitative behavior, depending on the relative values of the weight parameters. In certain cases, an individual flow with long-tailed traffic characteristics is effectively served at a constant rate. Asymptotically, the flow is then only influenced by the traffic characteristics of the other flows through their average rate. In particular, the flow is essentially immune from excessive activity of flows with `heavier'-tailed traffic characteristics. In other scenarios however, a flow may be strongly affected by the activity of `heavier'-tailed flows, and may inherit their traffic characteristics, causing induced burstiness. The stark contrast in qualitative behavior illustrates the crucial importance of the weight parameters.

Large Polling Systems with Heavy-Tailed Service and/or Switchover Times

Jacques Resing, Eindhoven University of Technology

Polling systems are queueing systems in which a single server visits several queues in some predescribed, e.g. cyclic, order. These systems have a wide range of applications, not only in computer-communications, but also in manufacturing and traffic. In view of the role of polling in computer-communication networks, it is important to study the effect of heavy-tailed service and/or switchover time distributions on the tail behaviour of the waiting times in polling systems. In this talk we will discuss this tail behaviour for cyclic polling systems with Poisson arrivals, general independent service and switchover times and the gated or exhaustive service discipline. At each queue, customers are served in the order in which they arrive. Our main result is the following. If at least one of the service and/or switchover time distributions has a regularly varying tail of index $-\nu$ ($\nu > 1$) and the others have a lighter tail, then the waiting time distribution at each queue has a regularly varying tail of index $1-\nu$.

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