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Computer Performance Evaluation

Modelling Techniques and Tools

12th International Conference, TOOLS 2002
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Preface

The argument for performance engineering methods to be employed in computer-communication systems has always been that such systems cannot be designed or modified efficiently without recourse to some form of predictive model, just as in other fields of engineering. This argument has never been more valid than it is with today's highly complex combination of communication and computer technologies. These have created the internet, the grid, and diverse types of parallel and distributed computer systems. To be practical, performance engineering relies on tools to render its use accessible to the non-performance specialist, and in turn these depend on sound techniques that include analytical methods, stochastic models, and simulation. Tools and techniques also need to be parameterised and validated against real world observations, requiring sophisticated measurement techniques in the picosecond cyber-world. The series of "International Conferences on Modelling Techniques and Tools for Computer Performance Evaluation" (TOOLS) has provided a forum for this community of performance engineers with all their diverse interests. TOOLS 2002, held in London in April 2002, was the continuation of this series, which comprises:

1984 Paris	1991 Torino	1997 Saint Malo
1985 Sophia Antipolis	1992 Edinburgh	1998 Palma
1987 Paris	1994 Wien	2000 Chicago
1988 Palma	1995 Heidelberg	2002 London

This year we were fortunate to have two prominent invited speakers, Onno Boxma, Eindhoven University of Technology, and Peter Key of Microsoft Research, Cambridge. In addition, an invited tutorial was given by Erol Gelenbe, University of Central Florida, one of the leading researchers in Performance Modelling. A total of 57 papers were submitted, including 9 tools proposals. At the Programme Committee meeting in January, 18 excellent papers were considered to be of high enough quality to be accepted, along with 6 tools presentations. The number of tools presentations was somewhat lower than at previous conferences in the series, probably due to the new constraints imposed requiring open source software. These were introduced to facilitate greater ease of dissemination and collaboration. All of the accepted papers have been included in this volume, 10 of them in extended form, up to 20 pages long.

The conference was organised into a single track comprising eight sessions of mixed topics. Some of the papers addressed generic techniques, for example related to Stochastic Process Algebra and the analysis of Petri Nets and Markov Chains. Others concerned the development and practical application of tools in areas such as the Internet, Software Performance Engineering, Parallel and Real-time Systems, and Transaction Processing.

In addition to the 18 main papers, the volume also includes a reduced (up to 6-page) paper for each tool presented.

It is a pleasure for the Program Chairs to acknowledge the staunch efforts made by many to make this conference possible and ensure its success. The whole Program Committee worked tirelessly on a very tight timescale to produce sufficient reviews in time for the meeting in mid-January, only seven weeks after the final submission deadline. There were at least three reviews for every submission and some even had five. Moreover, the large majority gave a careful, in-depth opinion. The same applies to several external referees that supported committee members.

In particular, we wish to thank the following for their administrative, organisational, and IT contributions, without which the schedule could not have been implemented, there would have been nowhere for participants to stay, and we would not have had the superb social events arranged at the *London Eye* and *Bistro 190*:

- Dave Nichol for writing WIMPE and advising us
- Dave Thornley for local arrangements
- Imperial College and the Department of Computing in particular, for hosting the conference and providing technical support
- Denise Grant for helping us to organise the finances

February 2002

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Tools 2002 was organised by the AESOP group of the Department of Computer Science, Imperial College, London.

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Table of Contents

Heavy Tails: The Effect of the Service Discipline

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Abstract. This paper considers the $M/G/1$ queue with regularly varying service requirement distribution. It studies the effect of the service discipline on the tail behavior of the waiting- or sojourn time distribution, demonstrating that different disciplines may lead to quite different tail behavior. The orientation of the paper is methodological: We outline three different methods of determining tail behavior, illustrating them for service disciplines like FCFS, Processor Sharing and LCFS.

This paper is dedicated to the memory of Vincent Dumas, a dear friend and gifted young mathematician.

1 Introduction

Measurements indicate that traffic in high-speed networks exhibits burstiness on a wide range of time scales, manifesting itself in long-range dependence and self-similarity, see for instance Leland *et al.* [29], Paxson & Floyd [38]. The occurrence of these phenomena is commonly attributed to extreme variability and long-tailed characteristics in the underlying activity patterns (connection times, file sizes, scene lengths), see for instance Beran *et al.* [5], Crovella & Bestavros [20], Willinger *et al.* [43]. This has triggered a lively interest in queueing models with long-tailed traffic characteristics.

Although the presence of long-tailed traffic characteristics is widely acknowledged, the practical implications for network performance and traffic engineering remain to be fully resolved. An interesting aspect is the role of scheduling and priority mechanisms in controlling the effect of long-tailed traffic characteristics on network performance. In a fundamental paper, Anantharam [3] considered a single-server queue fed by a Poisson arrival process of sessions, with each session lasting for an independent integer time T for which holds: $\mathbf{P}\{T = k\} \sim \alpha k^{-(\alpha+1)} L(k)$, where $1 < \alpha < 2$ and $L(\cdot)$ is a slowly varying function (see Definition 1). Each session brings in work at unit rate while it

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is active. Hence, the work brought in by each arrival is regularly varying and, because $1 < \alpha < 2$, the arrival process of work is long-range dependent, but $\mathbf{E}T < \infty$. Anantharam shows that, in the steady-state case, for *any* stationary Non-Preemptive service policy at the queue, the stationary sojourn time of a typical session must stochastically dominate a regularly varying random variable having infinite mean. Non-preemption means that once service on a session has begun, it is continued until all the work associated with it has been completed. Anantharam does not make any assumptions as to whether the service policy is work-conserving, or whether the length of a session is known at the time of arrival. In marked contrast to the above, Anantharam also shows that there exist causal stationary *preemptive* policies, which do not need information about the session durations at the time of their arrival, for which the stationary sojourn time of a session is stochastically dominated by a regularly varying random variable with finite mean.

The results of Anantharam raise several questions, like (i) are there (preemptive) service disciplines for which the tail of the sojourn time distribution is not heavier than the tail of the service requirement distribution, and (ii) what is the effect of various well-known scheduling disciplines on the tail behavior of the waiting- or sojourn time distribution?

A related issue arises when there are *several classes* of customers, which may be treated in different ways by the server (e.g., using fixed priorities, or according to a polling discipline). Then it is important to understand under what conditions, or to what extent, the tail behavior of the service requirements of one class affects the performance of other classes. The above issues have recently been investigated by the present authors and some of their colleagues. This paper summarizes the results. We focus on the classical $M/G/1$ queue and its multi-class generalizations (although some of the recently obtained results allow a general renewal arrival process, or a fluid input).

The orientation of the paper is methodological. After introducing the model and reviewing the main results for various basic disciplines in Section 2, we discuss three different methods of obtaining the tail behavior of waiting- or sojourn time distributions for $M/G/1$-type queues with regularly varying service requirement distribution(s): (i) an analytical one, which relies on Tauberian theorems relating the tail behavior of a probability distribution to the behavior of its Laplace-Stieltjes transform near the origin; (ii) a probabilistic one, which exploits a Markov-type inequality, relating an extremely large sojourn (or waiting) time with a single extremely large service requirement; and (iii) a probabilistic one, which is based on sample-path arguments which lead to lower and upper bounds for probability tails. These three approaches are the topics of Sections 3, 4 and 5, respectively. Sections 3 and 5 also discuss the multi-class case.

2 Model Description and Main Results

In this section, we formally describe the model, introduce some concepts and notation, and give an overview of the main results.

As stated before, we focus on the $M/G/1$ queue. In this system, customers arrive according to a Poisson process, with rate λ, at a single server who works at unit rate. Their service requirements $B_1, B_2, \ldots$ are independent and identically distributed, with distribution $B(\cdot)$ with mean β and Laplace-Stieltjes Transform (LST) $\beta\{\cdot\}$. A generic service requirement is denoted by B. There is no restriction on the number of customers in the system. We assume that the offered traffic load $\rho := \lambda\beta < 1$, so that the system reaches steady state. We study the stationary sojourn time S of a customer, and in some cases also the stationary waiting time W until service begins.

Before surveying the tail asymptotics of the waiting-time and sojourn time distributions for various service disciplines, we first introduce some useful notation and terminology. For any two real functions $g(\cdot)$ and $h(\cdot)$, we use the notational convention $g(x) \sim h(x)$ to denote $\lim_{x\to\infty} g(x)/h(x) = 1$, or equivalently, $g(x) = h(x)(1+o(1))$ as $x \to \infty$. For any stochastic variable X with distribution function $F(\cdot)$, with $\mathbf{E}X < \infty$, denote by $F^r(\cdot)$ the distribution function of the residual lifetime of X, i.e., $F^r(x) = \frac{1}{\mathbf{E}X}\int_0^x (1 - F(y))\mathrm{d}y$, and by X^r a stochastic variable with distribution $F^r(\cdot)$.

Throughout this paper, we focus on the class $\mathcal{R}$ of *regularly-varying* distributions (which contains the Pareto distribution). This class is a subset of the class of subexponential distributions [27], that contains, a.o., the lognormal and Weibull distributions.

Definition 1. A distribution function $F(\cdot)$ on $[0, \infty)$ is called *regularly varying of index* $-\nu$ ($F(\cdot) \in \mathcal{R}_{-\nu}$) if

$$1 - F(x) = x^{-\nu}L(x), \quad \nu \geq 0,$$

where $L : \mathbb{R}_+ \to \mathbb{R}_+$ is a function of slow variation, i.e., $\lim_{x\to\infty} L(\eta x)/L(x) = 1$, $\eta > 1$.

The class of regularly varying functions was introduced by Karamata [25], and its potential for probability theory was extensively discussed in Feller [23]. A key reference is Bingham *et al.* [7].

In the remainder of this section, we present an overview of the tail asymptotics of the waiting-time and sojourn time distributions in the $M/G/1$ queue for six key disciplines: (i) First-Come-First Served (FCFS); (ii) Processor Sharing (PS); (iii) Last-Come-First-Served Preemptive-Resume (LCFS-PR); (iv) Last-Come-First-Served Non-Preemptive Priority (LCFS-NP); (v) Foreground-Background Processor Sharing (FBPS); (vi) Shortest Remaining Processing Time First (SRPTF).

(i) The $M/G/1$ FCFS queue

The next theorem characterizes the tail asymptotics of the distribution of the steady-state waiting time W for the FCFS service discipline.