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## Dynamic Allocation and Admission Policies for QoS-aware Provisioning Systems

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**Abstract:** We present an architecture of a hosting system consisting of a set of hosted Web Services subject to QoS constraints, and a certain number of servers used to run users demand. The traffic is session-based, while provider and users agree on SLAs specifying the expected level of service performance such that the service provider is liable to compensate his/her customers if the level of performance is not satisfactory. The system is driven by a utility function which tries to optimize the average earned revenue per unit time. The middleware collects demand and performance statistics, and estimates traffic parameters in order to make dynamic decisions concerning server allocation and admission control. We empirically evaluate the effects of admission policies, resource allocation and service differentiation schemes on the achieved revenues, and we find that our system is robust enough to successfully deal with session-based traffic under different conditions.

**Keywords:** Utility Functions, Data Centers, Autonomic Systems, Web Services, Middleware.

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#### Biographical notes:

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**Manuel Mazzara** achieved his Masters in 2002 and his Ph.D in 2006 at the University of Bologna. His thesis was based on Formal Methods for Web Services Composition. During 2000 he was a Technical Assistant at Computer Science Laboratories (Bologna, Italy). In 2003 he worked as Software Engineer at Microsoft (Redmond, USA). In 2004 and 2005 he worked as a free lance consultant and teacher in Italy. In 2006 he was an assistant professor at the University of Bolzano (Italy) and in 2007 a researcher and project manager at the Technical University of Vienna (Austria). Currently he is a Research Associate at the Newcastle University (UK) working on the DEPLOY project.

**Nicola Dragoni** obtained a M.Sc. Degree and a Ph.D. in computer science, respectively in 2002 and 2006, both at University of Bologna, Italy. He visited the Knowledge Media Institute at the Open University (UK) in 2004 and the MIT Center for Collective Intelligence (USA) in 2006. In 2007 and 2008 he was post-doctoral research fellow at University of Trento, working on the security for mobile systems. Between 2005 and 2008 he also worked as freelance IT consultant. In 2009 he joined Technical University of Denmark (DTU) as assistant professor in security and distributed systems. Since May 2011 he has been associate professor at the same university.

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## 1 Introduction

The increasing use of the Internet as a provider of services and a major information media has changed significantly, in the last decade, users expectations in terms of performance. It is simply considered no longer acceptable to wait a number of seconds to access a service or an information. Users, these days, expect a browser to perform like a home TV or a radio, completely ignoring the basic differences between the functioning behind, and sometime cultivating unrealistic desires, especially regarding failures and robustness. This is one of the consequences of interpreting IT systems as information providers (due to the explosions of sites like Wikipedia or on-line encyclopedias) instead of a means for running calculations, as occurred 10 or 15 years ago. A perfect example of this situation is described in Linden (2006) and Shankland (2008): they found out that an extra 0.5 seconds in search page generation would kill user satisfaction, with a consequent 20% traffic drop (Linden (2006)), while trimming the page size of Google Maps by 30% resulted in a traffic increase of 30% (Shankland (2008)).

### 1.1 *Performance-related Social Aspects and IT Consequences*

During the events of September 11, 2001 almost every news website became unavailable for hours (LeFebvre (2001)) showing the weaknesses (but it would be better to say the differences) of the Internet compared to the traditional information media. Situations like these certainly require a deeper investigation of the social impact of such approach in information retrieval (and “keyboard dependency”) but this topic is definitely out of scope for this paper. Thus, given this “embedded human behavior”, IT scientists can only interpret this need as a new challenge for performance requirements: customers expect not only resilience (*i.e.*, the capacity of the system to recover from damage), but also performance. Besides, under-performing systems are rarely profitable.

These aspects easily trigger an important discussion regarding resilience and performance in this context. Given the higher and higher expectations in terms of

performance, how will an average user be able to distinguish between a slow service and a stuck or failed one? Although apart from Linden (2006) we are not aware of any other proper study in this field, it is not difficult to imagine that any under-performing system will simply be ignored and treated like a failed one. Thus, in the authors' point of view, it would be simply unrealistic to consider resilience and performance as two characteristics that can be analyzed separately. The nature of the problem forces us to consider Quality of Service (QoS) as part of system robustness. Our opinion is that the issues related to service quality will eventually become a significant factor in distinguishing the success or the failure of service providers.

## *1.2 Technology Adopted and Motivations*

Web Services are self-describing, open components that support rapid, low-cost composition of distributed applications. The system architecture presented in this work is based on this technology since their adoption looks like a promising solution to low cost and immediate integration with other applications and partners. The use of Web Services, in fact, eases the interoperability between different systems because they use open protocols and standards such as SOAP and HTTP. On the other hand, as this technology proliferates more and more widely, the issues related to service quality become very relevant and will eventually become a significant factor in distinguishing the success or the failure of service providers. Unfortunately, it is extremely difficult for service providers to meet the promised performance guarantees in the face of unpredictable demand. One possible approach is the adoption of Service Level Agreements (SLAs), contracts that specify a level of performance that must be met and compensations in case of failure. It is worth saying that the notions of compensations and failure here are different from the ones discussed in Lucchi and Mazzara (2007) and Dragoni and Mazzara (2009). Here the compensation is a penalty to pay and the failure is intended as a failure in meeting the specified level of performance, while there compensation was instead a process with a designer-dependent logic with the goal of partially recover a transaction made of a composition of different services. There are certainly analogies but a deeper investigation here it is not possible due to space constraints. The basic idea is that the theory presented in Mazzara and Lanese (2006) and the mechanism used there to dynamically trigger a compensation process can be exploited also to model the kind of scenarios presented in this work but with the evident open issue of time modelling (this topic has been discussed in Mazzara (2005)).

## *Paper Contribution and Organization*

This paper addresses some of the performance problems arising when IT companies sell the service of running jobs subject to QoS, and thus robustness, constraints. We focus on session-based traffic because, even though it is widely used (*e.g.*, Amazon or eBay), it is very difficult to handle; session-based traffic requires ad-hoc techniques, as job-based admission control policies drop requests at random and thus all clients connecting to the system would be likely to experience connection failures or broken sessions under heavy load, even though there might be capacity on the system to serve all requests properly for a subset of clients. Also, since active sessions can be aborted at any time, there could be an inefficient use of resources because aborted sessions do not perform any useful work, but they waste the available resources.

The contributions of the paper are threefold. First, we provide a formal model describing the problem we want to tackle, that is to measure and optimize the performance

of a QoS-aware service provisioning system in terms of the average revenue received per unit time. According to this model, we then propose and implement an SLA-driven service provisioning system running jobs subject to QoS contracts. The middleware collects demand and performance statistics, and estimates traffic parameters in order to make dynamic decisions concerning server allocation and admission control. The system architecture presented in this work is based on Web Services technology and when we mention the word “service” we actually mean the specific technology. Anyway, this is just an implementation choice that we will explain later. Other solutions would be certainly possible. Finally, we evaluate and validate our proposal through several experiments, showing the robustness of our approach under different traffic conditions.

The rest of the paper is organized as follows. Relevant related work is discussed in Section 2, the problem we want to tackle is formally modelled in Section 3 and policies for dynamic reconfiguration are discussed in Section 4. Section 5 then presents the system’s architecture and discusses how the system deals with session-based traffic, while Section 6 presents a number of experiments we have carried out. Finally, Section 7 concludes the paper highlighting possible directions for future work.

## 2 Related Work

There is an extensive literature on adaptive resource management techniques for commercial data centers (*e.g.*, Rajkumar et al. (1997), Ghosh et al. (2003), Hansen et al. (2004) to mention only a few). Yet, since previous work does not take into account the economic issues related to SLAs, service providers would still need to over-provision their data centers in order to address highly variable traffic conditions. Moreover, existing studies do not consider admission policies as a mechanism to protect data centers against overload conditions (LeFebvre (2001)). However, as will become clear later in this paper, admission control algorithms have a significant effect on revenues.

The problem of autonomously configuring a computing cluster in order to satisfy SLA requirements is addressed in several papers. Some of them consider the economic issues occurring when services are offered as part of a contract, however they do not address the problems affecting overloaded server systems (*e.g.*, Chandra et al. (2003), Li et al. (2005), Zhang and Ardagna (2004)), while others include simple admission control schemes without taking any economic parameter into account.

Finally, while there is an extensive literature on request-based admission control (*e.g.*, Urgaonkar et al. (2005), Mazzucco et al. (2007)), session-based admission control is much less well studied. Also, nobody has studied the effects of combining admission control, resource allocation and economics when trying to model a commercial service provisioning system subject to QoS constraints. For example, Villela et al. (2007), Urgaonkar et al. (2005) and Levy et al. (2003) consider some economic models dealing with single jobs, but they focus on allocating server capacity only, while admission policies are not taken into account. Yet, revenues can be improved very significantly by imposing suitable conditions for accepting jobs. To our knowledge, the most closely related work is perhaps Mazzucco et al. (2007), that studies the effects of SLAs and allocation and admission policies on the maximum achievable revenues in the context of individual jobs. However, in E-business systems such as Amazon or eBay, requests coming from the same customer are related and thus they can be grouped into sessions. Unfortunately, if admission control policies like the one discussed in Mazzucco et al. (2007) are in operation,

a user trying to execute several related jobs would not know in advance whether all jobs will be accepted or not. In this paper, instead, we implement some admission policies specifically designed to deal with session-based traffic; our approach uses a combination of admission control algorithms, service differentiation, resource allocation techniques and economic parameters to make the service provisioning system as profitable as possible.

### 3 Problem Formulation

In this section we present a mathematical model of the real world problem we intend to tackle. The reason for having a formal model is to abstract from the details we do not want to investigate, focusing only on those that are of interest for this work. The risk of formal models is always the over abstraction of problems; furthermore, interactions between aspects that are included in the model and aspects that are excluded can complicate the situation. We intend to keep the model manageable and thus the proposed model is based on the concept of utility functions, a simple and common way for achieving self-optimization in distributed computing systems. While different kinds of utility functions can be employed, in this paper the average revenue obtained by the service provider per unit time is the considered metric. In a nutshell, the model can be defined as follows: the user agrees to pay a specified amount for each accepted session, and also to submit the jobs belonging to it at a specified rate. On the other hand, the provider promises to run all jobs belonging to the session, and to pay a penalty if the average performance for the session falls under a certain threshold.

More formally, the provider has a cluster of  $N$  servers, used to run  $m$  different type of services, while the traffic is session-based. A session is defined as follows:

**Definition 3.1 (Session)** *A session of type  $i$  is a collection of  $k_i$  jobs, submitted at a rate of  $\gamma_i$  jobs per second.*

One strong assumption behind this model is the request of *session integrity* (i.e., if a session is accepted, all jobs in it will be executed), as it is critical for commercial services. From a business perspective, the higher the number of completed sessions, the higher the revenue is likely to be, while the same does not apply to single jobs. Apart from the penalties resulting from the failure to meet the promised QoS standards, sessions that are broken or delayed at some critical stages, such as checkout, could mean loss of revenue for the service owners. From a customer's point of view, instead, breaking session integrity would generate a lot of frustration because the service would appear as not reliable. We assume that the QoS experienced by an accepted session of type  $i$  is measured by the observed average waiting time:

$$W_i = \frac{1}{k_i} \sum_{j=1}^{k_i} w_j, \quad (1)$$

where  $w_j$  is the waiting time of the  $j$ th job of the session, i.e., the interval between its arrival and the start of its service. Also, we assume that the provisioning contract includes an SLA specifying clauses related to charge, obligation and penalty.

**Definition 3.2 (Charge)** *For each accepted session of type  $i$ , a user shall pay a charge of  $c_i$ .*

How to determine the amount of charge for each successfully executed session is outside the scope of this paper. However, intuitively, this could depend on the number of jobs in the session,  $k_i$ , and their submission rate,  $\gamma_i$ , or on the obligation. It is certainly expected that for stricter obligations there will be higher charges.

**Definition 3.3 (Obligation)** *The observed average waiting time,  $W_i$ , of an accepted session of type  $i$  shall not exceed  $q_i$ .*

**Definition 3.4 (Penalty)** *For each accepted session of type  $i$  whose average waiting time exceeds the obligation (i.e.,  $W_i > q_i$ ), the provider is liable to pay to the user a penalty of  $r_i$ .*

While the performance of computing systems can be measured using different metrics, in this paper we are interested in the average revenue received per unit time, as it is more meaningful from a business perspective than values such as the throughput or average response times. Thus, as far as the provider is concerned, the performance of the system is measured by the average revenue,  $R$ , received per unit time. That quantity can be computed using the following expression:

$$R = \sum_{i=1}^m a_i [c_i - r_i P(W_i > q_i)]. \quad (2)$$

About Equation (2), it is perhaps worth noting that while it resembles the utility function discussed in Mazzucco et al. (2007), here  $a_i$  refers to the average number of type  $i$  sessions that are accepted into the system per unit time, while  $P(W_i > q_i)$  is the probability that the observed average waiting time of a type  $i$  session exceeds the obligation  $q_i$ . Also, while no assumption about the relative magnitudes of charges and penalties is made, the problem is interesting mainly if  $c_i \leq r_i$ . Otherwise one could guarantee a positive (but not optimal) revenue by accepting all traffic, regardless of loads and obligations. Finally, Equation (2) uses a “flat penalty” factor: if  $W_i > q_i$  the provider must pay a penalty  $r_i$ , no matter what the amount of the delay is. Such a model can be easily extended. For example, one could introduce penalties that are proportional to the amount by which the waiting time exceeds the obligation  $q$  (the effect of that would be to replace the term  $P(W_i > q_i)$  in Equation (2) with  $E(\min(0, W_i - q_i))$ ).

Finally, instead of allocating whole servers to one of the  $m$  offered services, the provider might want to share servers between different job types. If this is the case, it is possible to control the fraction of service capacity each service type is entitled to use, for example via block of threads. Those threads would thus play the role of servers.

## 4 Policies for Dynamic Reconfiguration

Because of the random nature of Internet traffic and changes in demand pattern over time, accurate capacity planning is very difficult in the short time period and almost impossible in the long time period. On the other hand, if servers are statically assigned to the provided services, some of them might get overloaded, while others might be underutilized. It is clear that in such scenarios it could be advantageous to reallocate unused resources to oversubscribed services, even at the cost of switching overheads, either in terms of time or money.

The question that arises in that context is how to decide whether, and if so when, to perform such system dynamic reconfiguration. Posed in its full generality, this is a complex problem which does not always yield an exact and explicit solution. Thus, it might be better to use some heuristic policies which, even though not optimal, perform reasonably well and are easily implementable. Within the control of the host are the “resource allocation” and “job admission” policies. The first decides how to partition the total number of servers,  $N$ , among the  $m$  service pools. That is, it assigns  $n_i$  servers to jobs of type  $i$  ( $n_1 + n_2 + \dots + n_m = N$ ). The allocation policy may deliberately make the decision to deny service to one or more job types (this will certainly happen if the number of offered services exceeds the number of servers). The server allocation policy is invoked at session arrival and session completion instants, while the admission policy is invoked at session arrival instants in order to decide whether the incoming session should be accepted or rejected. Of course, the allocation and admission policies are coupled: admission decisions depend on the allocated servers and vice versa. Moreover, they should be able to react to changes in user demand.

During the intervals between consecutive policy invocations, the number of active sessions remains constant. Those intervals, which will be referred to as “observation windows”, are used by the controlling software in order to collect traffic statistics and obtain current estimates, as the queueing analysis carried out at each configuration epoch requires estimates of the average arrival rates ( $\lambda_i$ ) and service times ( $b_i$ ), and squared coefficient of variation of request interarrival ( $ca_i^2$ ) and services times ( $cs_i^2$ ). Please note that all of the above parameters are time varying and stochastic in nature, and thus their values should be estimated at each configuration interval. However, if the estimates are accurate enough, the arrival rates and service times can be approximate as independent and identically distributed (i.i.d.) random variables inside each window, thus allowing for online optimizations.

In this paper, we implement and experiment with various heuristic policies. As allocation algorithm we use the ‘Offered Loads’ heuristic (see Fig. 1), a simple adaptive policy that, using the traffic estimates collected during the previous observation window, allocates the servers roughly in proportion to the offered loads,  $\rho_i = \lambda_i b_i$ , and to a set of coefficients,  $\alpha_i$ , reflecting the economic importance of the different job types (for service differentiation purposes):

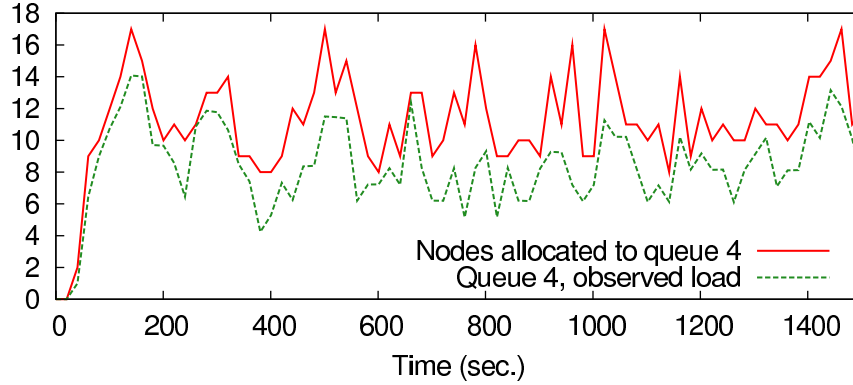
$$n_i = \left\lfloor N \frac{\rho_i \alpha_i}{\sum_{j=1}^m \rho_j \alpha_j} + 0.5 \right\rfloor, \quad (3)$$

(adding 0.5 and truncating is the round-off operation). Then, if the sum of the resulting allocations is either less or greater than  $N$ , adjust the number of allocated servers so that they add up to  $N$ .

For admission purposes we have embedded into our system three heuristics, ‘Current State’, ‘Threshold’ and ‘Long-Run’. The first two algorithms are formally described in Mazzucco et al. (2008), and thus we only summarize them here. The ‘Current State’ policy estimates, at every arrival epoch, the changes in expected revenue, and accepts the incoming session (possibly in conjunction with a reallocation of servers from other queues) only if the change in expected revenue is positive. In order to compute that value, it uses the state of each queue, which is specified by the number of currently active sessions, the number of completed jobs and average waiting time achieved so far (for each session).

The ‘Threshold’ heuristic uses a threshold,  $M_i$ , for each job type, and an incoming session is accepted into the system only if less than  $M_i$  sessions are active. Each threshold





**Figure 1** Dynamic resource allocation. Resources are allocated in proportion to the measured load.

$M_i$  is chosen so as to maximize  $R_i$ . We have carried out some numerical experiments, and found that  $R_i$  is a unimodal function of  $M_i$ . That is, it has a single maximum, which may be at  $M_i = \infty$  for lightly loaded systems. That observation implies that one can search for the optimal admission threshold by evaluating  $R_i$  for consecutive values of  $M_i$ , stopping either when  $R_i$  starts decreasing or, if that does not happen, when the increase becomes smaller than some  $\epsilon$ . Such searches are typically very fast.

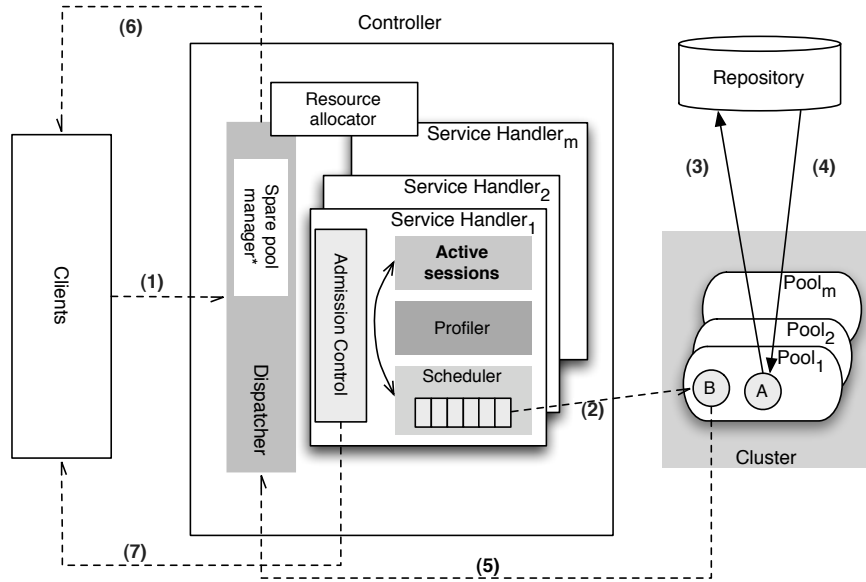
Finally, the ‘Long-Run’ heuristic assumes that jobs of type  $i$  are submitted with the same arrival rate, that all sessions of type  $i$  have the same number of jobs, and that each queue is subject to a constant load of sessions  $L_i$ . Suppose that queue  $i$  is subjected to a constant load of  $L_i$  streams (*i.e.*, as soon as one session completes, a new one replaces it) and has  $n_i$  servers allocated to it. Since each session consists of  $k_i$  jobs submitted at rate  $\gamma_i$ , the average period during which a session is active is roughly  $k_i/\gamma_i$  while, from Little’s theorem, the rate at which streams are initiated is  $L_i\gamma_i/k_i$ . The above observations imply that, if over a long period, the numbers of active streams in the system are given by the vector  $L = (L_1, L_2, \dots, L_m)$ , and the server allocation is given by the vector  $n = (n_1, n_2, \dots, n_m)$ , the total expected revenue earned per unit time can be computed using Equation (2), where the average number of type  $i$  sessions accepted per unit time,  $a_i$ , is replaced by  $L_i\gamma_i/k_i$ .

## 5 System Architecture

Today’s service provisioning systems are usually designed according to a three-tier software architecture. The first layer translates end-user markup languages into and out of business data structures, the second tier performs computation on business data structures while the third level provides storage functionality. Requests traverse tiers via synchronous communication over local area networks and a single request may revisit tiers more than once. Business-logic computation are often the bottleneck for Internet services, and thus this paper focuses on this tier. However, user-perceived performance depends also on disk and network workloads at other tiers. Front-end servers are not typically subject to a very high workload, and thus over-provision is usually the cheapest solution to meet service quality requirements. Moreover, different solutions exist to address some of the issues

occurring at both the presentation and database tiers (Stewart and Shen (2005); Doyle et al. (2003)), while McWherter et al. (2004) have shown that smart scheduling can improve the performance of the database tier.

The three-tier software architecture presented in this work is based on Web Services technology. Web Services are self-describing, open components that support rapid, low-cost composition of distributed applications and their adoption looks like a promising solution to low cost and immediate integration with other applications and partners. The use of Web Services, in fact, eases the interoperability between different systems because they use open protocols and standards such as SOAP and HTTP. Computing systems are usually designed according to this three-tier software architecture (front-end, business logic and storage) but in this paper we focus mainly on the second one, as business logic computation is often the bottleneck for Internet services. Of course, user-perceived performance depends also on disk and network workloads at other tiers. However, front-end servers are not typically subject to a very high workload, and thus over-provision is usually the cheapest solution to meet service quality requirements, while different solutions exist to address some of the issues occurring at both the presentation and database tiers (see Stewart and Shen (2005) and Doyle et al. (2003) for more details).



**Figure 2** Architecture overview. Dotted lines indicate asynchronous messages.

The architecture we propose, shown in Figure 2, uses a dedicated hosting model and follows the mediation service pattern (Hohpe and Woolf (2004)). The middleware hides the IT infrastructure from the clients, creating an illusion of a single system by using a Layer-7 two-way architecture (Cardellini et al. (2002)), while the load balancer uses a packet double-rewriting algorithm (*i.e.*, it forwards packets in both directions, client-to-server and server-to-client) and takes routing decisions using only the information available at the application layer of the OSI stack, such as target URL or cookie. This makes adding or removing servers at runtime straightforward, as clients do not know where their requests

will be executed. All incoming jobs are sent to the Controller (arrow 1), which performs the resource allocation, admission control and monitoring functions. For each type of service there is a corresponding Service Handler, which schedules incoming jobs for execution, collects traffic statistics through a profiler, and manages the currently allocated pool of servers. If the admission policy does not require global state information (*e.g.*, threshold-based policies), then it too may be delegated to the Service Handlers. If the same service is offered at different QoS levels and a threshold-based admission policy is employed, the Service Handler will be instantiated at differentiated service levels. Each level will have its own SLA management function instantiated that strives to meet that level of service specified by the differentiation. If the load is too high for any of the differentiated services, then the admission policy will start rejecting incoming traffic in order to maintain an adequate level of performance. For policies that take into account the state of all queues at every decision epoch (*i.e.*, state-based policies), instead, there is no need to use different Service Handlers to deal with different QoS levels, as sessions can specify their own QoS requirements.

### *Session Arrival*

Here we discuss the steps taken at session arrival instants by state-based policies. In order to guarantee the correctness of the computation (multiple threads could see the system in different states), consecutive requests are serialized by using a pipeline with a single executor. Every time a new session of type  $i$  enters the system, the program sketched in Algorithm 1 is executed. The algorithm first estimates the current arrival rates and the potential arrival rates if the session was accepted (the only arrival rate which changes is the one of queue  $i$ , line 3), and simulates a new server allocation using the potential arrival rates (line 4). Then it computes the expected change in revenue,  $\Delta R$ . The decision of accepting the new session, eventually with a reallocation of servers from other queues to queue  $i$ , would increase the amount of charges by  $c_i$ , but it will also increase the arrival rate at queue  $i$  by  $\gamma_i$ . Thus, if the session was accepted, there would be a possible penalty of  $r_i$  in case the performance of the new session was not met, and also different probabilities of paying penalties for all the active sessions.

Denote by  $g(x, \lambda, k, n)$  the probability that the average waiting time for  $k$  jobs exceeds the threshold  $x$ , given that the arrival rate is  $\lambda$  and that there are  $n$  servers. Having defined  $g(\cdot)$ , the expected change in revenue resulting from a decision to switch servers among queues and to accept a new session is computed in lines 5–12 as:

$$\Delta R = c_i - r_i g(q_i, \lambda_i + \gamma_i, k_i, n'_i) - \sum_{j=1}^m r_j \sum_{t=1}^{L_j} \Delta g_j(\cdot_t), \quad (4)$$

where  $\Delta g_j(\cdot_t)$  is the change in probability of paying a penalty for session  $t$  at queue  $j$ , see line 9, while  $L_j$  is the number of active sessions at queue  $j$ . For session  $t$  at queue  $j$ , the number of completed jobs is identified by  $l_t$ , while the average waiting time over those jobs is  $u_t$ . Thus, the overall waiting time that should not be exceeded over the remaining  $k_j - l_t$  jobs, trouble a penalty of  $r_j$ , is

$$q_{j,t} = \frac{q_j k_j - u_t l_t}{k_j - l_t}. \quad (5)$$

**Input** : A session arriving at queue  $i$ ,  $s_i$   
**Output**: The cookie for the session, if accepted,  $-1$  otherwise

```

1 Phase I: Estimate  $\Delta R$ ;
2  $(\lambda_1, \dots, \lambda_m) \leftarrow \text{EstimateCurArrRate}();$ 
3  $(\lambda'_1, \dots, \lambda'_m) \leftarrow (\lambda_1, \dots, \lambda_{i-1}, (\lambda_i + \gamma_i), \lambda_{i+1}, \dots, \lambda_m);$ 
4  $(n'_1, \dots, n'_m) \leftarrow \text{SimulateAllocation}(\lambda'_1, \dots, \lambda'_m);$ 
5  $\Delta R \leftarrow c_i - [r_i \times g(q_i, \lambda'_i, k_i, n'_i)];$ 
6 for  $j \leftarrow 1$  to  $m$  do
7   foreach session  $t$  in queue  $j$  do
8      $q_{j,t} \leftarrow \frac{q_j k_j - u_t l_t}{k_j - l_t};$ 
9      $\Delta g_j \leftarrow g(q_{j,t}, \lambda'_j, k_j - l_t, n'_j) - g(q_{j,t}, \lambda_j, k_j - l_t, n_j);$ 
10     $\Delta R \leftarrow \Delta R - (r_j \times \Delta g);$ 
11   end
12 end
13 Phase II: generate the cookie and re-allocate servers;
14 if  $\Delta R > 0$  then
15    $\text{cookie} \leftarrow \text{GenerateCookie}(i);$ 
16    $\text{AddSession}(\text{queue}_i, \text{session});$ 
17    $\text{SetAllocation}(n'_1, \dots, n'_m);$ 
18 else
19    $\text{cookie} \leftarrow -1;$ 
20 end
21 return  $\text{cookie};$ 

```

**Algorithm 1:** Session arrival, state-based policies.

At the end of the for loop, if the expected change in revenue is positive the new session is accepted, the cookie is generated, and server reallocation is put in operation (lines 14–17). Otherwise, the session is rejected and the server reallocation remains unchanged, see line 19.

### 5.1 Job Execution

Apart from running the job, the only responsibility of the target machine is to save the cookie before running the job and to ‘attach’ it to the header of the response once the job has completed. When a response of type  $i$  belonging to stream  $j$  arrives, the dispatcher ‘forwards’ it to the  $i$ th Service Handler. The handler gets the cookie identifying the stream as well as the service and waiting time values from the response object, and passes this 3-tuple to the object storing the current state of the handler, via the `completion()` method. This increments the number of completed jobs and decreases the number of pending jobs of type  $i$ , and updates the global average values for type  $i$  jobs. Finally, it invokes `completion()` on stream  $j$  with the service and waiting times as arguments. If the stream is completed, the `State` computes whether a penalty should be paid or not (*i.e.*, if the SLA was met or not), then it removes stream  $j$  from the set of the active sessions. If a state-based policy is in operation, the allocation task is executed every time a session completes.

## 6 Experiments

Several experiments were carried out in order to evaluate the robustness of our approach under different traffic conditions. However, because of space constraints, only some of them are discussed here. As discussed in Section 3, the metric of interest is the average revenue earned per unit time. CPU-bound jobs, whose lengths and arrival instants were randomly generated, queued and executed. We use synthetic load as this makes it easier to experiment with different traffic patterns. Moreover, we abstract from the hardware details such as number of cores or amount of memory; this way a job takes the same time everywhere, no matter on which hardware it is executed. Apart from the random network delays, messages are subject to random processing overhead, which cannot be controlled. Also, it could not be guaranteed that the servers were dedicated to these tasks, as there could be random demands from other users. The server capacity is guaranteed by a cluster of 20 (identical) servers running Linux with kernel 2.6.14, Sun JDK 1.5.0\_04, Apache Axis2 1.3 (to handle SOAP messages) and Tomcat 5.5 (to handle HTTP requests). The connection between the load generator and the controller is provided by a 100 Mb/sec Ethernet network, while the servers of the cluster are connected to the controller via a 1 GBit/sec Ethernet network. Each server can execute only one job at any time, *i.e.*, the system does not allow processor sharing. The scheduling policy is FIFO, with no preemption, while servers allocated to queue  $i$  cannot be idle if there are jobs of type  $i$  waiting. Finally, messages are sent using the HTTP protocol, as this is the most widely used protocol to exchange SOAP messages over the Internet. In order to reduce the number of variables, the following parameters were kept fixed:

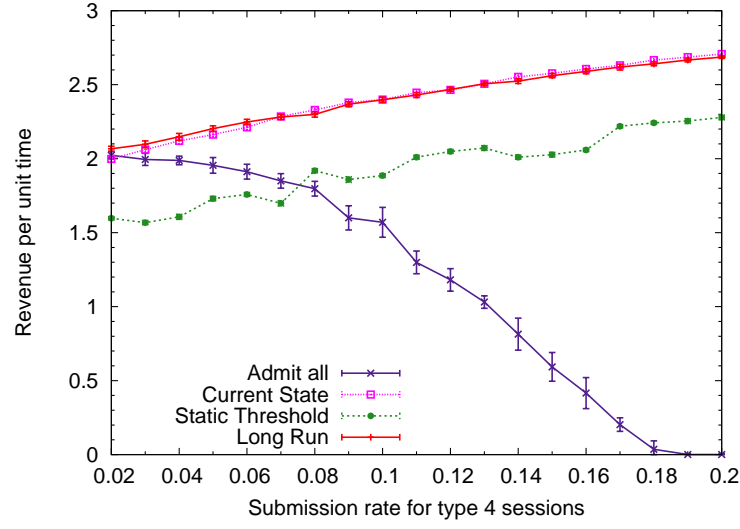
- The server capacity is guaranteed by a cluster of 20 servers offering four job types, *i.e.*,  $N = 20$ ,  $m = 4$ .
- The obligations undertaken by the provider are that the average observed waiting time of the session should not exceed the average required service time, *i.e.*,  $q_i = b_i$ .
- All sessions consist of 50 jobs, *i.e.*,  $k = 50$ . The job arrival rates are  $\gamma_1 = \gamma_2 = \gamma_3 = 2$ , while that for type 4 is  $\gamma_4 = 1$ . The average service time for all jobs is  $b = 1$ .
- Sessions are submitted with rate  $\delta_1 = 0.1$ ,  $\delta_2 = 0.04$  and  $\delta_3 = 0.08$ .
- The total offered load ranges between 60% to over 100% (*i.e.*, the system would be overloaded if all sessions were accepted) by varying the submission rate of type 4 jobs,  $\delta_4 \in (0.02, 0.2)$ .

### *Markovian Traffic Scenario*

In the following two experiments we assume that the traffic is Markovian, that is, the sessions and jobs enter the system according to independent Poisson processes, while service times are exponentially distributed.

### *Charges = Penalties.*

The first experiment, shown in Figure 3, measures the average revenues obtained by the heuristic policies proposed in Section 4 when all charges and penalties are the same, *i.e.*,



**Figure 3** [Experiment 1] Observed revenues when  $c_i = r_i = 10, \forall i$ .

$c_i = r_i, \forall i$ : if the average waiting time exceeds the obligation, users get their money back. For comparison, the effect of not having an admission policy is also displayed.

Each point in the figure represents a run lasting about 2 hours. In that time, between 1,400 (low load) and 1,700 (high load) sessions of all types are accepted, corresponding to about 70,000 – 85,000 jobs. Samples of achieved revenues are collected every 10 minutes and are used at the end of the run to compute the corresponding 95% confidence interval (Student's  $t$ -distribution was used). The most notable feature of this graph is that while the performance of the 'Admit all' policy becomes steadily worse as soon as the load increases and drops to 0 when it approaches the saturation point, the heuristic algorithms produce revenues that grow with the offered load. According to the information we have logged during the experiments, they achieve that growth not only by accepting more sessions, but also by rejecting more sessions at higher loads.

### Other Metrics

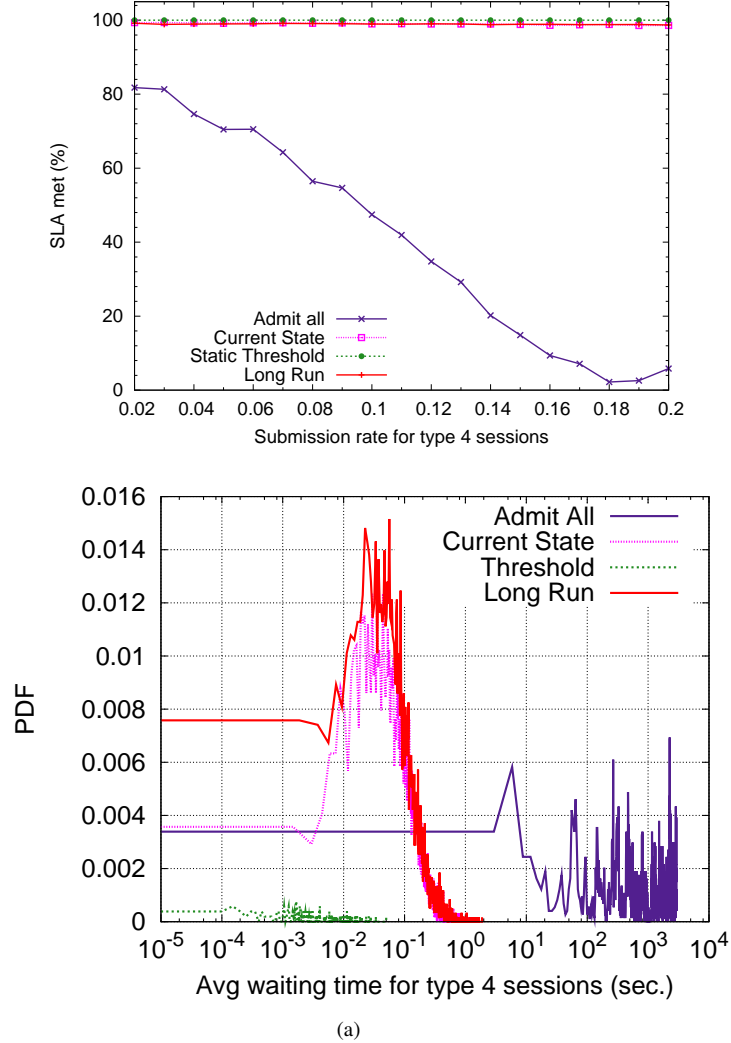
In some cases, values other than the average revenue per unit time might be of interest. A possible example is the rate at which the sessions of type  $i$  are rejected, or the percentage of accepted sessions whose performance falls below the minimum promised performance levels. For the 'Threshold' heuristic, the former is given by:

$$X_i = \lambda_i p_{i,M_i}, \quad (6)$$

where  $p_{i,M_i}$  is the probability that a session of type  $i$  is rejected, that is, that there are  $M_i$  active sessions in the  $i$ th queue (no mathematical formula exists for the state-based policies).

Also, the performance of the various policies can be better understood by observing other metrics; a policy might under-perform either because it accepts too many sessions, thus failing to deliver the promised QoS (like the 'Admit All' policy in Fig. 6), or

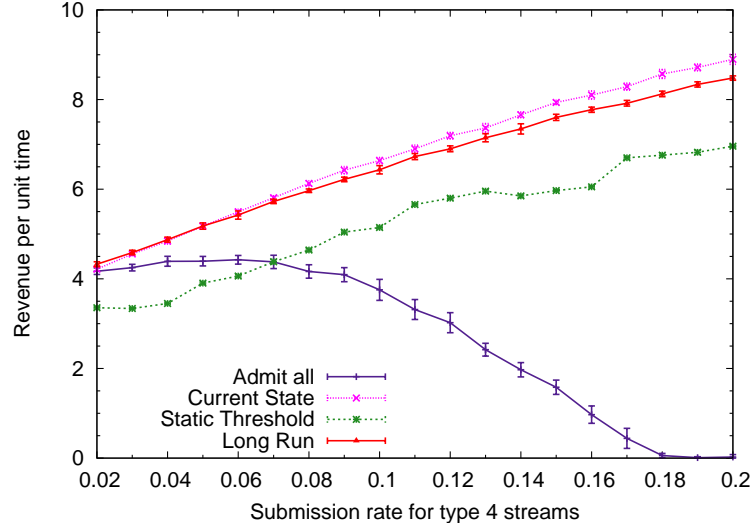
because it rejects too many sessions, thus missing income opportunities, like in the case of the ‘Threshold’ policy. Fig. 4(a) shows very clearly that the ‘Threshold’ policy is very conservative, as almost all of the accepted sessions experience an average waiting time of less than 0.1 seconds, while the minimum acceptable performance level is set to 1 second.



**Figure 4** [Experiment 1] Other metrics: (a) SLA met for different policies, and (b) Probability density function (PDF) of the observed average waiting time for type 4 sessions,  $\delta_4 = 0.2$ .

The second result concerns a similar experiment, except that now charges and related penalties differ between each job type:  $c_1 = 10$ ,  $c_2 = 20$ ,  $c_3 = 30$  and  $c_4 = 40$ ,  $c_i = r_i$ . The main difference compared to the previous experiment is that now it is more profitable to run, say, jobs of type 4 than jobs of type 3. Figure 5 shows that the maximum achievable revenues are now much higher than before in virtue of the higher charge values for type

2, 3 and 4 streams. Moreover, the ‘Long Run’ heuristic still performs very well, while the difference between the ‘Current State’ and the ‘Threshold’ policies is about 25%.



**Figure 5** [Experiment 2] Observed revenues when  $c_1 = 10, c_2 = 20, c_3 = 30, c_4 = 40, r_i = c_i$ .

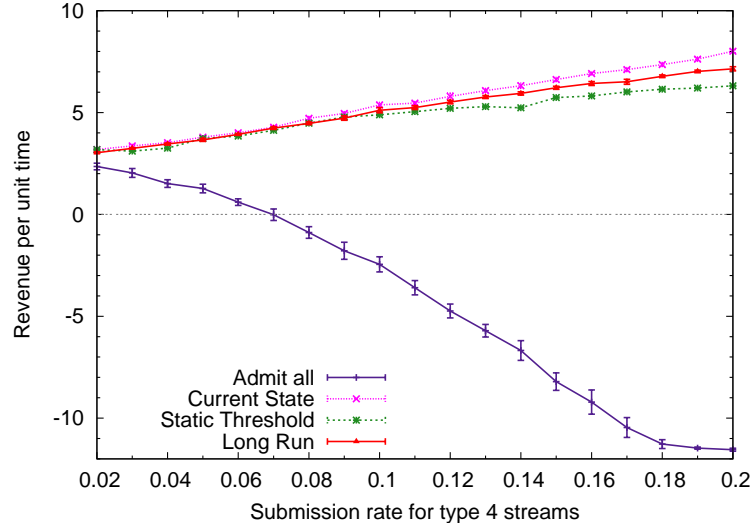
### High Variability Scenario

Next, we depart from the assumption that traffic is Markovian. A higher variability is introduced by generating jobs with hyperexponentially distributed service times: 80% of them are short, with mean service time 0.2 seconds, and 20% are much longer, with mean service time 4.2 seconds. The overall average service time is still 1 second, but the squared coefficient of variation of service times is now 6.15, *i.e.*  $cs^2 = 6.15$ . The aim of increasing variability is to make the system less predictable and decision making more difficult. The charges are the same as in Figure 5, however if the SLA is not met, users get back twice what they paid, *i.e.*,  $r_i = 2c_i$ . The most notable feature of the graph shown in Figure 6 is that now the revenues obtained by the ‘Admit all’ policy become negative as soon as the load starts increasing because penalties are very punitive. On the other hand, the behavior of the three policies is similar. The ‘Current State’ and ‘Long Run’ algorithms performs worse than in the Markovian case (with  $r_i = 2c_i$ , not shown), while the wise ‘Threshold’ heuristic performs almost the same way. Similar results were obtained in the case of bursty arrivals. They are not shown here for the sake of space.

## 7 Conclusions and Future Work

In this paper we have presented a SLA-driven Service Provisioning System running jobs subject to QoS contracts. The system uses a utility function whose aim is to maximize the average revenue earned per unit time. We have demonstrated that policy decisions such





**Figure 6** [Experiment 3] Observed revenues for different policies and two-phase hyperexponentially distributed service times:  $cs_i^2 = 6.15$ ,  $r_i = 2c_i$ , charges as in Figure 5.

as server allocations and admission control can have a significant effect on the revenue. Moreover, those decisions are affected by the contractual obligations between clients and provider in relation to the QoS. The experiments we have discussed show that our system can successfully deal with session-based traffic under different traffic conditions. Possible directions for future research include sharing a server among several types of services or expensive system reconfigurations, either in terms of money or time (Amazon EC2, for example, can take up to 10 minutes to launch a new instance). Also in order to further improve the efficiency of the available servers, a concurrency level higher than one could be used. Of course, since the SLAs are still in operation, it is not possible to change the concurrency level at random: instead, the same QoS level as if jobs were ran alone should be maintained. Finally, one might want to increase the capacity of a data center by allowing it to be composed by several clusters. Such clusters may belong to the same organization or to different entities.

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