Providing Absolute Differentiated Services with Statistical Guarantees in Static Priority Scheduling Networks

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Abstract

In this paper, we propose and analyze a methodology for providing absolute differentiated services with statistical performance guarantees for real-time applications in networks that use static priority schedulers. We extend the previous work on the delay analysis and develop a method that can be used to derive statistical delay guarantees in a flow-unaware fashion. While traditional delay analysis methods depend on flow population information, we have developed a method that relies on network (re-)configuration time analysis, and allows us to analyze the delays without depending on the dynamic status of flow population.

With this new method, we are able to reduce the runtime admission control to a simple utilization test. No explicit delay computation is necessary at admission time making this approach scalable to large systems.

Keywords — *absolute differentiated services, statistical service, real-time application, static priority scheduling, utilization-based admission control.*

Contents

1 Introduction

In this paper, we study a methodology for providing *absolute differentiated services* with *statistical performance guarantees* in networks that use static priority schedulers. We extend previous results on delay analysis with statistical guarantees from an `IntServ` framework to a `DiffServ` environment with no flow awareness. We hence are able to provide a solution that is practical and effective.

1.1 Statistical Absolute Differentiated Services

The recent development of the differentiated service (`DiffServ`) Internet model is aimed at supporting service differentiation for aggregated traffic in a scalable manner. Traditionally, differentiated services seek to provide per-hop, per-class relative services [5]. Consequently, the network does not provide guarantees for end-to-end real-time services such as the case in `IntServ`. Instead, each router only guarantees that the service invariant is *locally* maintained, even though the absolute end-to-end service might vary with networking conditions. A number of approaches have been proposed to provide `IntServ`-like end-to-end absolute performance measures without per-flow information in the network core. For example, assuming that no dynamic routing occurs, the premium service can offer the user a performance level that is similar to that of a leased-line, as long as the user's traffic is limited to a given bandwidth [16]. We call this type of service *absolute differentiated services*.

For absolute differentiated services, performance guarantees are either deterministic or statistical. *Deterministic services* support applications that have stringent performance requirements for a service with zero packet drops or delay bound violations [1, 2, 6, 14]. While they provide a very simple service model to the application, deterministic services, by their very nature, tend to heavily overcommit resources because they reserve resources according to a worst-case scenario. In real networks, most of time, this often results significant portions of network resources (bandwidth etc.) being wasted [23].

Statistical services, on the other hand, exploit stochastic properties of traffic flows. They allow a pre-defined portion of packets to miss their deadlines, and therefore provide *probabilistic performance guarantees*. Statistical services significantly increase the efficiency of network use by allowing increased statistical multiplexing of the underlying network resources. This comes at the expense of packets to be occasionally dropped or excessively delayed. In this papers we will show how such probabilistic guarantees can be provided in a differentiated services framework.

1.2 Admission Control

In order to provide any form of service guarantees, an admissioncontrol mechanism has to be in place, which makes sure that enough resources are available to satisfy the requirements of both the new and the existing connections after the new connection has been admitted. In order to keep steps with the scalability requirements for differentiated services networks, any admission control mechanism must be extremely light-weight so that can be realized in a scalable fashion. We show how, through appropriate system (re-)configuration steps, the delay guarantee tests at run-time can be reduced to simple utilization-based test: as long as the utilization of links along the path of a flow is not beyond a given bound, the probabilistic performance guarantee can be met. The value of the utilization bound is verified at system (re-)configuration time. Once verified, the use of this utilization bound is relatively simple at flow admission time: Upon the arrival of a flow establishment request, the admission control admits the flow if the utilization values of links along the path of the new flow are no more than the bound. Thus, this approach (called Utilization-Based Admission Contrl – UBAC – in the following) eliminates explicit delay analysis at admission time, and helps the system scale up.

Utilization-based admission control (UBAC) is not new to networks. The fluid-flow model in the `IntServ` gramework, for example, allows various forms of utilization based admission control [18]. Such approaches cannot be used in a `DiffServ` framework, however, because they rely on guaranteed-rate schedulers, which need to maintain flow information. In this paper, we adopt the approach to the UBAC method in [22]. The challenge of using the UBAC method is how to verify the correctness of a utilization bound at the configuration time. Obviously, the verification will have to be involved with delay analysis. We adopt the similar approach in [11] to do statistical delay analysis. However, the delay violation probability derived in [11] depends on the information of flow population. To extend it to be in `DiffServ` fashion, we will develop a method that allows us to analyze the delays without depending on the dynamic status of flow population.

Progress has been made to provide statistical performance guarantees in `IntServ` [1, 8, 9, 11, 12, 17, 20, 25, 26], but no such results are available for absolute statistical performance guarantees in `DiffServ`. Our approach is based on a simple and general traffic characterization which is called *rate-variance envelope* [10, 11]; this envelope describes the variances of the flows' rates as a function of interval length. We will consider networks that use static priority scheduler. Given that static priority scheduling is supported in many current routers (e.g., RowerRail Routing Switch, produced by Packet Engines), our approach can be easily implemented in the existing networks. As expected, our experimental data show that statistical services can achieve much higher utilization than deterministic services.

The rest of the paper is organized as follows. In Section 2, we describe previous work on absolute differentiated services and statistical service in general. The underlying network and traffic models for this study are introduced in Section 3. In Section 4, we develop a delay analysis methodology that is insensitive to flow information. In Section 5, we provide extensive experimental data to illustrate that the utilization achieved within a statistical model is much higher than within a deterministic model. A summary of the paper is given in Section 6.

2 Previous Works

A good survey to the recent work on absolute differentiated services has been done in [19]. Nicols et. al. [16] propose the *premium service model*, which provides the equivalent of a dedicated link between two access routers. It provides absolute differentiated services in priority-driven scheduling networks with two priorities, in which the high priority is reserved for premium service. The algorithm in [3] provides both guaranteed and statistical rate and delay bounds, and addresses scalability through traffic aggregation and statistical multiplexing. Stoica and Zhang describe an architecture to provide guaranteed service without per-flow state management by using a technique called dynamic packet state (DPS) [21]. Our work is based on static-priority scheduling algorithm, which is relatively simple and widely supported.

Statistical service has been studied via envelopes of bounding moment generating functions [1], exponentially bounded envelopes [20, 25], and envelopes consisting of families of bounding distributions [12, 26]. Statistical envelopes have also been applied to resource allocation for inter-class resource sharing [17] and video-on-demand services [8]. Much work has been done to generalize schedulabilty conditions for a deterministic service to a probabilistic framework. Several researchers made probabilistic extensions to deterministic service models. In [9, 11], a *rate-variance envelope* is introduced, which describes the variance of the arrivals of a flow as a function of a time period of length. In [9], arrivals on a flow are assumed to be characterized by the rate-variance envelope and a long-term arrival rate. Then, applying the a central limit theorem argument, a bound for the probability of a delay bound violation is derived for a static priority scheduler. In [11], the same framework is used to address bounds on the rate-variance envelope for regulated, adversarial traffic sources. In [10], the authors use a rate-variance envelope as a simple way to capture the second-moment properties of temporally correlated traffic flows, and to describe how quickly the rate-distribution becomes concentrated at the mean rate with increasing interval-length, a key factor for computing delay-bound-violation probabilities. They show empirical rate-variance envelopes for several long traces of compressed video to show how it captures the burstiness properties of realistic network traffic sources. In this paper, we will use this rate-variance envelope to do statistical delay analysis.

Admission control has been investigated widely [4, 7, 14]. The various approaches differ from each other in that they may require different scheduling schemes and so can be of vastly diffferent complexity. For example, traditional admission control in networks with static priority scheduling is very complicated. Due to absence of flow separation, for any new flow request, admission control needs to explicitly compute and verify delays for the new and existing flows. This procedure is very expensive with increasing numbers of flows. The Utilization-Based Admission Control (UBAC) adopted dramatically reduces this complexity.

In its basic form, UBAC was first proposed in [13] for preemptive scheduling of periodic tasks on a simple processor. A number of utilization-based tests are known for centralized systems(e.g., 69% and 100% for periodic tasks on a single server using rate-monotonic and earliest-deadline-first scheduling, respectively[13]), or distributed systems(such as 33% for synchronous traffic over FDDI networks [27]). In this paper, we adopt utilization-based tests in providing differentiated services in static priority scheduling networks.

3 Network and Traffic Models

In this section, we describe the model and define the terminology that will be used in the rest of this paper.

3.1 Network Model

The `DiffServ` architecture distinguishes two types of routers: *Edge routers* are located at the boundary of the network, and provide support for traffic policing. *Core routers* are within the interior of the network. Routers are connected through *links*, which – for simplicty's argument – we assume to be all of capacity C, in bits per second. We denote L_k the set of input links for Sever k.

When we compute delays, we follow standard practice and model a router as a set of *servers*, one for each router component, where packets can experience delays. Packets are typically queued at some of these services, typically output buffers, where they compete for the output link. We, therefore, model a router as a set of output *link servers*. All other servers (input buffers, non-blocking switch fabric, wires, etc.) can be eliminated by appropriately subtracting constant delays incurred on them from the deadline requirements of the traffic.

3.2 Traffic Model

We call a stream of packets between a sender and receiver a *flow*. Packets of a flow are transmitted along a single path, which we model as a list of link servers. Following the `DiffServ` architecture, flows are partitioned into classes. QoS requirements and traffic specifications of flows are defined on a class-by-class basis. We use M to denote the total number of classes in a network. We assume that at each link server, a certain percentage of bandwidth is reserved for each particular traffic class. Let $\alpha_{q,k}$ denote the percentage of bandwidth reserved for Class q at server k. It is the responsibility of the admission control module to ensure that the bandwidth usage of individual classes does not go beyond the reserved portion. This is necessary to provide isolation among classes and hence to guarantee end-to-end delays to the flows in each class. In a router with static-priority schedulers, packets are served based on their priorities. In our model, different classes have different priorities. Packets with higher priorities will be served prior to those with lower priorities.

We use the following two traffic descriptors to characterize the traffic:

Definition 1 (Deterministic Arrival Traffic Envelope) *The traffic function $a(\tau)$ is defined as the amount of the traffic in the group of flows G during time interval $[0, \tau)$. The function $b(t)$ is called the deterministic arrival traffic envelope of $a(\tau)$ if*

$$a(\tau + t) - a(\tau) \leq b(t). \tag{1}$$

for any $\tau > 0$ and $t > 0$.

Definition 2 (Statistical Arrival Traffic Envelope) *If the incoming traffic amount of the traffic in the group of flows G during time interval $[0, \tau)$ is a random variable $\mathcal{A}(\tau)$, then the distribution $B(t)$ forms the stochastic arrival traffic envelope of $\mathcal{A}(\tau)$ if*

$$\mathcal{A}(\tau + t) - \mathcal{A}(\tau) \leq_{st} B(t), \tag{2}$$

for any $\tau > 0$ and $t > 0$, where $X \leq_{st} Y$ means $P\{X > Z\} \leq P\{Y > Z\}$ [12].

In this paper, we consider the rate-variance envelope, which describes the variance of the arrival traffic rate during a time interval. The rate-variance envelope $RV(t)$

describes the variance of the arrival rate for the group of flows G over an intervals of length t [10], i.e.

$$RV(t) = var\left(\frac{\mathcal{A}(\tau+t) - \mathcal{A}(\tau)}{t}\right). \tag{3}$$

In the following, we will use the notation $G_{i,j,k}$ to denote a group of flows of Class i going through Server k from input link j and use $b_{i,j,k}$, $B_{i,j,k}$, and $RV_{i,j,k}$ to specify the deterministic arrival traffic envelope, the stochastic arrival traffic envelope, and the rate-variance envelope applied to the group of flow $G_{i,j,k}$ respectively.

4 Providing Absolute Differentiate Services with Statistical Guarantees

4.1 Overview

In the following, we will use a utilization based test to realize admission control in a scalable fashion. During system (re-)configuration a utilization bound is determined, which is then used for the tests during run time. As long as the utilization values of links along the path of a new flow does not exceed the value for the utilization bound, the probabilistic performance guarantee can be met. The value for the utilization bound depends on network topology, traffic characteristics, and performance requirements of flows.

The challenge of using any UBAC method is to verify the correctness of a utilization bound at configuration time. Two critical issues have to be addressed:

- Statistical Delay Analysis: The main challenge for statistical delay analysis is how to clearly describe the traffic arrival process. The strong assumptions on the stochastic properties of traffic streams are inherently difficult for the network to enforce or police. Consequently, if a particular application does not conform to the chosen stochastic model, no guarantees can be made. Moreover, if admitted to the network, such a stream could adversely affect the performance of other applications if it is statistically multiplexed with them. In this paper, we will use the approach in [11] to do the statistical delay analysis.
- Flow-Population-Insensitive Delay Analysis: Generally speaking, the delay violation probability derived in [11] depends on the information about flow population, i.e., the number of flows at input links and the traffic characteristics (e.g., the average rate and burst size) of flows. However, in our case the delay analysis is done at the system configuration time, when information about flow population is not available. Hence, it is necessary to derive a flow-population-insensitive formula. We will apply an approach similar to that used in [22] for deterministic traffic to solve this.

In the following subsections, we will focus on a single link server. Our approach is applicable across multiple network nodes by using a technique to that used in [9].

4.2 Statistical Delay Analysis at Configuration Time

First, we will address the issue of statistical delay analysis, and then derive the flow-population-insensitive statistical delay formula.

4.2.1 Statistical Delay Analysis

A probabilistic performance guarantee can be defined as a bound on the probability of exceeding a deadline as follows:

$$P\{D > d\} \leq \epsilon. \tag{4}$$

where the delay D suffered by a packet is a random variable, d is the given deadline, and ϵ is the given violation probability, which is generally small.

In statistical service, all input traffic conforms to a set of random processes. Suppose these processes are independent. If we know the mean value and the variance of each individual traffic random variable, and the number of flows is large enough, then by *Central Limit Theorem*, we can approximate the random process of the combined flows. The *Central Limit Theorem* states that the summation of a set of independent random variables converges in distribution to a random variable that has a *Normal Distribution.* Actually, using rate-variance envelopes, the traffic arrival rate of each individual flow is a random variable, and the mean rate and the rate-variance of each individual flow can be determined using deterministic traffic models. The following theorem can be found in [11]:

Theorem 1 *Consider a static priority scheduler with link capacity C such that the traffic with Class i at Server k has an associated deadline $d_{i,k}$. Suppose that the group of flows $G_{q,j,k}$ has mean rate $\phi_{q,j,k}$ and rate-variance envelope $RV_{q,j,k}(I)$ for $q = 1, \ldots, i$, and $j \in L_k$. With application of a Gaussian approximation over intervals, the delay violation probability for a random packet with Class i at Server k is approximately bounded by*

$$\begin{aligned} P\{D_{i,k} > d_{i,k}\} \leq & \\ & \max_{t<\beta_{i,k}} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(C(t+d_{i,k}) - \mu_{i,k}(t))^2}{2\sigma^2_{i,k}(t)}\right), \end{aligned} \tag{5}$$

where

$$\mu_{i,k}(t) = (t+d_{i,k}) \sum_{q=1}^{i-1} \sum_{j\in L_k} \phi_{q,j,k} + t \sum_{j\in L_k} \phi_{i,j,k}, \tag{6}$$

$$\begin{aligned} \sigma^2_{i,k}(t) = & (t+d_{i,k})^2 \sum_{q=1}^{i-1} \sum_{j\in L_k} RV_{q,j,k}(t+d_{i,k}) \\ & + t^2 \sum_{j\in L_k} RV_{i,j,k}(t), \end{aligned} \tag{7}$$

$$\beta_{i,k} = \min\{t : \sum_{q=1}^{i-1} \sum_{j\in L_k} b_{q,j,k}(t) \leq Ct,\ t > 0\}. \tag{8}$$

By this theorem, the delay violation probability for any random packet can be computed approximately. In the above formula, the question left is how to get the values of *mean rate* and *rate-variance envelope*. In [11], two methods are presented for obtaining the rate-variance envelope:

- Adversarial Mode: the traffic arrival process conforms to a binomial distribution, where the rate-variance envelope is upper bounded.
- Non-adversarial Mode: the traffic arrival process conforms to a weighted uniform distribution, where the rate-variance envelope is approximated but non-worst-case.

Therefore, given the aggregated arrival traffic constraint function, we can specify the *mean rate* and the *rate-variance envelope* as follows:

Theorem 2 *If the aggregated arrival traffic constraint function $b_{i,k,j}(t)$ is given as follows*

$$b_{i,j,k}(t) = \begin{cases} Ct, & t \leq \tau_{i,j,k} \\ n_{i,j,k}(\sigma_i + \rho_i\ t), & t > \tau_{i,j,k} \end{cases} \tag{9}$$

where

$$\tau_{i,j,k} \quad = \quad \frac{n_{i,j,k}\sigma_i}{C - n_{i,j,k}\rho_i}. \tag{10}$$

Then, the mean rate $\phi_{i,j,k}$ is

$$\phi_{i,j,k} = n_{i,j,k}\rho_i, \tag{11}$$

and the rate-variance envelope is upper bounded by:

- *Adversarial Mode*

$$RV_{i,j,k}(t) \leq \begin{cases} 0, & t \leq \tau_{i,j,k} \\ \frac{1}{t}(n_{i,j,k})^2\rho_i\ \sigma_i, & t > \tau_{i,j,k} \end{cases} \tag{12}$$

- *Non-adversarial Mode*

$$RV_{i,j,k}(t) \approx \begin{cases} 0, & t \leq \tau_{i,j,k} \\ \frac{1}{12t}(n_{i,j,k})^2\rho_i\ \sigma_i, & t > \tau_{i,j,k} \end{cases} \tag{13}$$

The proof of Theorem 2 is given in Appendix A.

With Theorem 2, the delay violation formula reduces to determining the number of flows on each link and the parameters in deterministic traffic models. Actually, the only undetermined is the number of flows on each link. In the following subsections, we describe how we eliminate the dependency on the number of flows on each link. The result is a delay formula that can be applied without knowledge of the flow population.

4.2.2 Flow-Population-Insensitive Statistical Delay Analysis

As we described earlier, admission control at run-time makes sure that the link utilization allocated to each class of flows is not exceeded. The numbers of flows of Class i on all input links $N_{i,k}$ are therefore subject to the following constraint:

$$N_{i,k} = \sum_{j \in L_k} n_{i,j,k} \leq \frac{\alpha_{i,k}}{\rho_i}C, \tag{14}$$

where $\alpha_{i,k}$ is the ratio of the link bandwidth allocated to traffic of Class i at Server k. With this constraint, by (11), (12), and (13), the mean rate and the rate-variance can be upper-bounded. Therefore, the delay violation probability can be upper-bounded without information about the flow-population as the following theorem shows:

Theorem 3 *Consider a static priority scheduler with link capacity C such that the traffic with Class i at Server k has an associated deadline $d_{i,k}$. Suppose that the group of flows $G_{q,j,k}$ has a stochastic envelope $B_{q,j,k}(t)$ for all $q = 1, \ldots, i$ and all $j \in L_k$, then the delay violation probability for a random packet of Class i at Server k is bounded by*

- *Adversarial Mode*

$$P\{D_{i,k} > d_{i,k}\} \leq \frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2} \min_{t<\beta_{i,k}} \xi_{i,k}(t)), \tag{15}$$

- *Non-adversarial Mode*

$$P\{d_{i,k} > D_{i,k}\} \leq \frac{1}{\sqrt{2\pi}} \exp(-6 \min_{t<\beta_{i,k}} \xi_{i,k}(t)), \tag{16}$$

where

$$\xi_{i,k}(t) = \frac{(\eta_{i,k}t + \eta_{i-1,k}d_{i,k})^2}{\zeta_{i,k}t + \zeta_{i-1,k}d_{i,k}}, \tag{17}$$

$$\beta_{i,k} = \frac{1}{\eta_{i,k}} \sum_{q=1}^{i} \alpha_{q,k} \frac{\sigma_q}{\rho_q}, \tag{18}$$

$$\eta_{p,k} = 1 - \sum_{q=1}^{p} \alpha_{q,k}, \tag{19}$$

and

$$\zeta_{p,k} = \sum_{q=1}^{p} (\alpha_{q,k})^2 \frac{\sigma_q}{\rho_q}. \tag{20}$$

In (19) and (20), $p = i-1, i$.

This is the main result of this paper. We observe that the formula does not depend on the flow population. Hence it can be used for utilization bound verification at configuration time. In the following, we will give the proof. The basic idea is that using inequality (14), flow-population will be removed.

Proof: Substituting (11), (12) and (13) into (6) and (7), we have

$$\begin{aligned} C(t + d_{i,k}) - \mu_{i,k}(t) = \\ t(C - \sum_{q=1}^{i} \sum_{j \in L_k} n_{q,j,k}\ \rho_q) + \\ d_{i,k}(C - \sum_{q=1}^{i-1} \sum_{j \in L_k} n_{q,j,k}\ \rho_q), \end{aligned} \tag{21}$$

and

- Adversarial Mode

$$
\begin{aligned}
&\sigma^2_{i,k}(t) = \\
&\quad t \sum_{q=1}^{i} \sum_{j \in L_k} (n_{q,j,k})^2 \ \rho_q \ \sigma_q + \\
&\quad d_{i,k} \sum_{q=1}^{i-1} \sum_{j \in L_k} (n_{q,j,k})^2 \ \rho_q \ \sigma_q.
\end{aligned} \tag{22}
$$

- Non-adversarial Mode

$$
\begin{aligned}
&\sigma^2_{i,k}(t) = \\
&\quad \frac{1}{12}(\ t \sum_{q=1}^{i} \sum_{j \in L_k} (n_{q,j,k})^2 \ \rho_q \ \sigma_q + \\
&\quad d_{i,k} \sum_{q=1}^{i-1} \sum_{j \in L_k} (n_{q,j,k})^2 \ \rho_q \ \sigma_q \ ).
\end{aligned} \tag{23}
$$

By (14), we have

$$
\sum_{j \in L_k} n_{q,j,k} \ \rho_q \quad \leq \quad \alpha_q \ C, \tag{24}
$$

and

$$
\sum_{j \in L_k} (n_{q,j,k})^2 \ \rho_q \ \sigma_q \quad \leq \quad (\alpha_q \ C)^2 \ \frac{\sigma_q}{\rho_q}, \tag{25}
$$

Therefore,

- for the adversarial mode

$$
\frac{(C(t + d_{i,k}) - \mu_{i,k}(t))^2}{2\sigma^2_{i,k}(t)} \geq \frac{1}{2}\xi_{i,k}(t), \tag{26}
$$

- and for the non-adversarial mode

$$
\frac{(C(t + d_{i,k}) - \mu_{i,k}(t))^2}{2\sigma^2_{i,k}(t)} \geq 6\xi_{i,k}(t). \tag{27}
$$

where $\xi_{i,k}(t)$ is defined in (17). ■

As an illustrative example, we apply the above theorem in the case of two classes, one real-time class and one best-effort class. Suppose that $\alpha_k = \alpha_{1,k}$, $\sigma = \sigma_1$, $\rho = \rho_1$, $d_k = d_{1,k}$, $D_k = D_{1,k}$, $\xi_k(t) = \xi_{1,k}(t)$, $\beta_k = \beta_{1,k}$, for real-time class traffic. Simplifying the formula, we can get the following corollary:

Corollary 1 *In the case of two classes, one real-time class and one best-effort class, the delay violation probability for a random real-time class traffic packet at Server k is bounded by*

- *adversarial mode*

$$P\{D_k > d_k\} \leq \frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2} \min_{t<\beta_k} \xi_k(t)), \tag{28}$$

- *and for the non-adversarial mode*

$$P\{d_k > D_k\} \leq \frac{1}{\sqrt{2\pi}} \exp(-6 \min_{t<\beta_k} \xi_k(t)), \tag{29}$$

where

$$\xi_k(t) = \frac{((1-\alpha_k)t + d_k)^2}{{\alpha_k}^2 \frac{\sigma}{\rho} t}, \tag{30}$$

$$\beta_k = \frac{\alpha_k}{1-\alpha_k} \frac{\sigma}{\rho}. \tag{31}$$

Define the right hand side of (28) and (29) as ϵ_1 and ϵ_2. We can find that $\xi_k(t)$ reaches its minimum at $t = t_0 = \frac{d_k}{1-\alpha_k}$. By the property of function $\xi_k(t)$, we find

- if $\beta_k \geq t_0$, i.e., $\alpha_k \geq \frac{d_k}{\frac{\sigma}{\rho}}$, then

$$\begin{aligned} \epsilon_1 &= \frac{1}{\sqrt{2\pi}} \exp(-2 \frac{1-\alpha_k}{{\alpha_k}^2} \frac{d_k}{\frac{\sigma}{\rho}}) && (32) \\ \epsilon_2 &= \frac{1}{\sqrt{2\pi}} \exp(-24 \frac{1-\alpha_k}{{\alpha_k}^2} \frac{d_k}{\frac{\sigma}{\rho}}) && (33) \end{aligned}$$

- if $\beta_k < t_0$, i.e., $\alpha_k < \frac{d_k}{\frac{\sigma}{\rho}}$, then

$$\begin{aligned} \epsilon_1 &= \frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2} \frac{1-\alpha_k}{{\alpha_k}^3} (\alpha_k + \frac{d_k}{\frac{\sigma}{\rho}})^2) && (34) \\ \epsilon_2 &= \frac{1}{\sqrt{2\pi}} \exp(-6 \frac{1-\alpha_k}{{\alpha_k}^3} (\alpha_k + \frac{d_k}{\frac{\sigma}{\rho}})^2) && (35) \end{aligned}$$

By the above formulas, we know that as α_k decrease to below $\frac{d_k}{\frac{\sigma}{\rho}}$, ϵ_1 and ϵ_2 will quickly approach 0.

For deterministic model, by Theorem 4 in [24], a bandwidth ratio formula can be derived as follows:

$$\alpha_k = \frac{d_k}{\frac{\sigma}{\rho}}. \tag{36}$$

Therefore, the bandwidth ratio value in the deterministic model is a critical point to the one in statistical model. Below this value, the delay violation probability is quite small and quickly approach 0.

4.3 Verification of Utilization Bound

Having derived the flow-population-insensitive statistical delay formula, we can verify the utilization bound, and obtain the *worst-case achievable utilization.* By the *worst-case achievable utilization*, we refer to the maximum of total utilization bound for all classes. Under the condition that the probabilistic delay guarantee can be met, we can compute the WCAU.

For a given delay violation probability $\epsilon_{i,k}$, and deadline $d_{i,k}$, the delay quarantee is met when

$$P\{D_{i,k} > d_{i,k}\} \leq \epsilon_{i,k}. \tag{37}$$

By Theorem 3, for the adversarial mode, if we solve the equality

$$\frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2} \min_{t<\beta_{i,k}} \xi_{i,k}(t)) \leq \epsilon_{i,k}; \tag{38}$$

for the non-adversarial mode, if we solve the equality

$$\frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2} \min_{t<\beta_{i,k}} \xi_{i,k}(t)) \leq \epsilon_{i,k}, \tag{39}$$

the maximal $\sum_{q=1}^{i} \alpha_{q,k}$ will be the WCAU for Server k.

5 Experimental Evaluation

In this section, we evaluate the performance of the approaches discussed in the previous sections. We will first define a performance metric, and then describe the system configuration and present the performance results.

5.1 Experimental Model

- *Performance Metric* We are interested in two metrics:
  - WCAU: The *worst-case achievable utilization* (WCAU) is the maximum of total utilization bound for all classes. We use this metric to measure the performance of the systems.
  - Admission Probability: This is the probability that a flow is admitted in a stable system. The higher the admission probability, the better the network resources are being used, and the better the performance.
- *Traffic Model* We assume that traffic belongs to two classes. Class 1 traffic is voice traffic, with bursts of 640 bits, an average rate of 32kbit/sec. We assume that the deadline is 5msec. Class 2 traffic is is best-effort traffic, and is served at lower priority. We assume that requests for Class 1 flow establishment form a Poisson process with rate λ, and that Class 1 lifetimes are exponentially distributed with an average of 180 seconds. The flow behaviour of Class-2 flows does not affect the evaluation results, and is therefore not further modeled.
- *Evaluation Methods* The WCAU can be computed by (15) and (16) using simple binary search. The admission probability of systems we consider can be analyzed by queuing theory and fixed point method [15].

5.2 Numerical Results and Observations

In this sub-section, we report on performance results and make observations. Due to the limited space, we only present a limited number of cases here. However, we find that the conclusions we draw here generally hold for many other cases we have evaluated.

ϵ	WCAU		
	deterministic	adversarial	non-adversarial
0	0.250	0.000	0.000
10^{-10000}	–	0.052	0.180
10^{-6000}	–	0.067	0.232
10^{-500}	–	0.233	0.250
10^{-30}	–	0.250	0.256
10^{-3}	–	0.250	0.618

Table 1: Sensitivity of WCAU to Delay Violation Probability

5.2.1 Sensitivity of WCAU to Delay Violation Probability

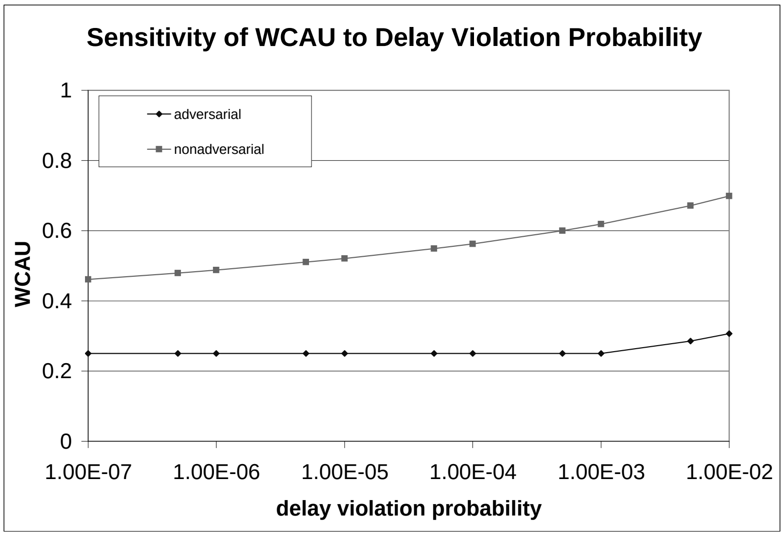

Figure 1: Sensitivity of WCAU to Delay Violation Probability

Data on sensitivity of utilization to delay violation probability are given in Figures 1 and Table 1. Figure 1 shows the data on the cases of the larger delay violation probability ϵ, and Table 1 shows the data on the cases of smaller ϵ. From Figures 1 and Table 1, we have the following observations:

- As expected, the utilization for both adversarial and non-adversarial model increas as the delay violation probability increases. This means that the higher delay violation probability, the higher utilization we can get for both adversarial and non-adversarial models. A higher delay violation probability allows for larger bandwidth allocations and, therefore, higher values for the WCAU.Both statistical models can achieve higher value for WCAU than the deterministic model when ϵ is not very small. Since the deterministic model does not allow delay violations, more resource needs to be reserved, which decreases WCAU.

- The Non-adversarial models achieves much higher WCAU than deterministic ones for any delay violation probability. Non-adversarial models are much closer to real traffic model, and much better exploit available statistical multiplexing gain.

5.2.2 Admission Probability Comparison of Deterministic and Statistical Model

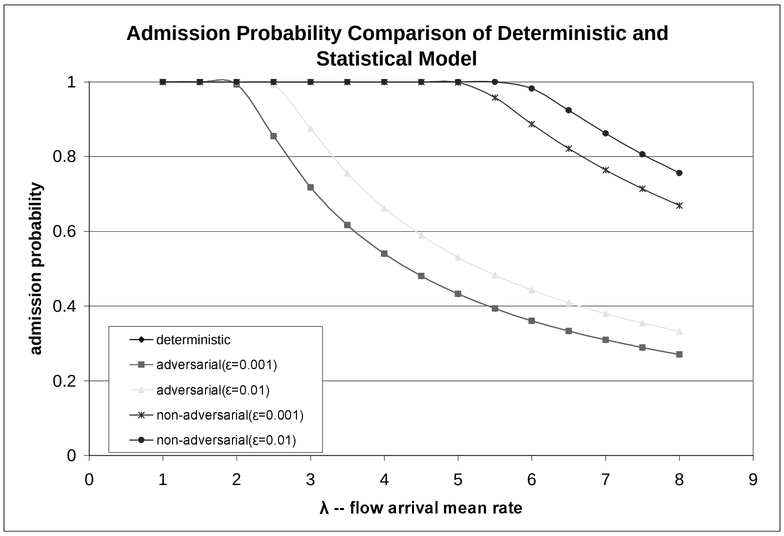

Figure 2: Admission Probability Comparison of Deterministic and Statistical Model

Data on sensitivity of admission probability is given in Figure 2. From this figure, we have the following observations:

- Admission probability is sensitive to the flow arrival rate λ for all models. Admission probability decreases as λ increases in all models. The reason is obvious: A large λ value implies a large number of flows in the system. Since the bandwidth is limited, some flows are not allowed to enter the network, therefore, the value of AP decreases.

- Different models have different sensitivities to λ in terms of admission probability. The statistic models alway achieve higher admission probabilities than the deterministic model; Non-adversarial models always achieve higher admission probabilities than Adversarial models. This is because of the achievable utilization. The higher this utilization, the higher admission probability.

6 Conclusions

In this paper, we have proposed a methodology for providing absolute differentiated services with *statistical* performance guarantees in networks that use static priority schedulers. Given that static priority schedulers are widely supported by current routers, we believe that our approach is practical and effective to support real-time applications in existing networks.

We have used Utilization-based Admission Control (UBAC) approach which uses a configuration-time verification to determine a safe utilization level of servers. Admission control at runtime then is reduced to simple utilization tests on the servers along the path of the new flow. Hence, the approach is scalable.

Obviously, the verification will have to be involved with delay analysis. The general delay derivation depends on flow population information, which is not available at the system configuration time. We have extended the general approach and developed a method that allows us to analyze the delays without depending on the dynamic status of flow population.

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Appendix A: Proof of Theorem 2

The following lemmas (1, 2, and 3) [11] give out a group of flows's mean rate and shows how its stochastic rate-variance envelope can be upper bounded from the deterministic parameters.

Lemma 1 (Mean Rate) *The mean rate of the group of flows $G_{i,j,k}$ can be defined as:*

$$\phi_{i,j,k} = \lim_{t \to \infty} \frac{b_{i,j,k}(t)}{t}. \tag{40}$$

Lemma 2 (Adversarial Mode) *The rate-variance envelope of the group of flows $G_{i,j,k}$ is upper bounded by:*

$$RV_{i,j,k}(t) \leq RV^*_{i,j,k}(t) = \phi_{i,j,k}(\frac{b_{i,j,k}(t)}{t} - \phi_{i,j,k}) \tag{41}$$

where $\phi_{i,j,k}$ is defined in (40).

Lemma 3 (Non-adversarial Mode) *The rate-variance envelope of the group of flows $G_{i,j,k}$ is appoximately:*

$$RV_{i,j,k}(t) \approx \widehat{RV}_{i,j,k}(t) = \frac{\phi_{i,j,k}}{12}(\frac{b_{i,j,k}(t)}{t} - \phi_{i,j,k}) \tag{42}$$

where $\phi_{i,j,k}$ is defined in (40).

We know that the aggregated arrival traffic constraint function $b_{i,k,j}(t)$ is given as follows

$$b_{i,j,k}(t) = \begin{cases} Ct, & t \leq \tau_{i,j,k} \\ n_{i,j,k}(\sigma_i + \rho_i\ t), & t > \tau_{i,j,k} \end{cases} \tag{43}$$

Then applying (43) to (40), (41), and (42), Theorem 2 can be proved as claimed.