QoS Provision and Routing with Stochastic Guarantees

Erez Biton and Ariel Orda *

Abstract

This work presents a methodology for providing QoS guarantees by considering the coupling between the scheduling mechanism and the routing schemes. Our main focus are rate-based schedulers and stochastic guarantees. We consider several traffic models and obtain for each an appropriate upper bound on the end-to-end delay tail distribution. With that at hand, we derive corresponding routing schemes that exploit the obtained bound. More specifically, we consider traffic with Exponentially Bounded Burstiness (EBB) and stochastic QoS requirements. First, we extend previous results and provide an upper bound on the tail distribution of the end-to-end delay for packetized traffic and links with non-negligible propagation delays. Consequently, we formulate several routing schemes that identify feasible paths under various network optimization criteria. We demonstrate the efficiency of these routing schemes via simulation examples. Then, we consider traffic with (general) stochastic bounded burstiness (SBB). Here, we provide the corresponding upper bound on the end-to-end delay tail distribution for packetized traffic and links with propagation delays. Finally, focusing on the special case of a bounding function that is the sum of exponents, we design appropriate routing schemes.

1. Introduction

Emerging Broadband high speed networks are expected to support real time and multimedia applications with various quality of service (QoS) requirements. One of the major problems in the provision of QoS guarantees is identifying a feasible path that can meet the QoS requirements. Worst case bounds on the backlog and delay constitute a valuable tool for quantifying the ability of a path to meet the QoS requirements. This study presents a methodology for providing QoS guarantees by considering the coupling between the scheduling mechanisms and routing schemes. We consider several traffic and link models and obtain for each appropriate end-to-end backlog and delay bounds. With these at hand, we derive corresponding efficient QoS routing schemes that exploit the obtained bounds.

The ability to support QoS requirements depends on the scheduling policies employed in the nodes. We focus on the "rate based" class [7, 21] and in particular on the Generalized Processor Sharing - GPS [13, 14] (also known as Weighted Fair Queuing) scheduling discipline. These disciplines provide isolation between sessions so that per session worst-case bounds on the backlog and delay, both for a single server in isolation and for networks with arbitrary topology, can be derived. Given these bounds, the corresponding routing problem is to identify the "best" path with respect to the QoS delay requirements.

In [7, 14, 21], networks with rate-based schedulers were studied under a deterministic setting, and worst-case bounds on the end-to-end delay were derived. The corresponding routing problem, of identifying the best path with respect to the QoS delay requirements, has been the subject of several studies, e.g. [8, 11, 12, 18]. In particular, it was shown in [8, 11] that for a given connection with end-to-end delay constraint, the existence and identity of a feasible path can be obtained through up to $M$ executions of a standard shortest path algorithm, where $M$ is the number of network links. In [12], a rate quantization method was employed, to establish a near-optimal solution for the basic problem of identifying a feasible route. The more general problem, of optimizing the route choice in terms of balancing the loads and accommodating multiple connections was considered as well, and several schemes were proposed.

Under a deterministic setting, the input traffic bursts are assumed to be of bounded length. This is not the case in most commonly used input processes. Hence, a setting that considers the stochastic nature of the traffic is desired. Under a stochas-

* Authors are with the Department of Electrical Engineering, Technion, Haifa, Israel. E-mail: {berez@tx,ariel@ee}.technion.ac.il
tic setting, only stochastic QoS is guaranteed, i.e., it is guaranteed that the end-to-end delay experienced by a high percentage of the packets does not significantly exceed the required delay. Such guarantees are appropriate for many applications, in particular multimedia applications, which can tolerate a certain amount of loss due to either late arrival or buffer overflow. With stochastic guarantees, tighter bounds and, consequently, better network utilization, can be achieved.

The statistical service curve approach [5, 20] provides a reasonably general framework for the statistical analysis of a variety of scheduling schemes, including the GPS discipline. It is based on a stochastic extension of the “service curve” concept developed by Cruz [4]. However, as observed in [16], it is not clear whether this framework can be extended to the multi-node case. Thus, we base our network analysis on the decomposition approach [22].

The statistical behavior of the GPS scheduling discipline using Exponentially Bounded Burstiness (EBB) processes [19] as source session traffic models, was studied in [22], and upper bounds on the tail distribution of session backlog and delay were derived, both for a single GPS server in isolation, as well as for Rate Proportional Processor Sharing (RPPS) GPS networks. [22] focused solely on “fluid” (non-packetized) GPS networks. We extend those results to packetized traffic and incorporate deterministic propagation delays in the network model. With these extended upper bounds at hand, we study the corresponding QoS routing problem. It turns out that this problem, though more complicated, resembles the routing problem under the deterministic setting.

In order to deal with processes that do not comply with the EBB characterization, a more general framework, of Stochastically Bounded Burstiness (SBB) traffic, was developed in [17], for an isolated network element. The SBB calculus is also a powerful tool for obtaining much tighter bounds for multiple time-scale processes. We adopt the SBB calculus of [17], and extend it in order to obtain bounds on the end-to-end delay tail distribution for a (packetized) RPPS PGPS network with propagation delays. Due to the complexity of the bounds, we establish routing schemes only for a special case of the SBB model, in which the bounding function is the sum of two exponents.

In [2], we also consider networks with variable-rate links. Specifically, we extend the results obtained in [10] for a single-input variable-rate server in isolation, in order to obtain a stochastic end-to-end delay bound for a packetized traffic entering a network with Exponentially Bounded Fluctuation (EBF) links and propagation delays. Then, we establish a corresponding routing algorithm.

Our stochastic model differs from that of [6, 9, 16, 20]. In our case, the stochasticness of the end-to-end guarantees is due to the stochastic nature of the session input traffic, whereas in [6, 9, 16, 20], the exploitation of statistical multiplexing results in a provision of (only) stochastic guarantees even for deterministically bounded input traffic.

The rest of the paper is structured as follows. In Section 2, we formulate the model. Next, in Section 3, we consider EBB processes: first, we establish bounds on the end-to-end delay tail distribution for a PGPS network with non-negligible propagation delays; then, we propose corresponding routing schemes and illustrate their efficiency through a simulation example. In Section 4, we consider the more general stochastic framework of SBB processes: we establish bounds on the end-to-end delay tail distribution and propose a routing scheme for a special case. Finally, in Section 5, we conclude the paper and discuss possible future work.

Due to space limits, all proofs as well as some details are omitted, and can be found in [2].

2. Model Formulation

Given is a network across which sessions need to be routed. The network is represented by a directed Graph $G(V,E)$, in which nodes represent switches and arcs represent links. $V$ is the set of nodes and $E$ is the set of interconnecting links; let $|V| = N$ and $|E| = M$.

Each link $l \in E$ is characterized by (i) a service rate $\overline{R}_l$ and (ii) a constant delay value $d_l$, related to the link’s speed, propagation delay and maximal transfer unit.

We assume that the Packetized Generalized Processor Sharing (PGPS) scheduling discipline is employed in each link $l \in E$ to ensure a guaranteed share of link resources. Since each link is associated with a (PGPS) server, we shall henceforth use the terms “server” and “link” interchangeably. We note that, if the service rate is a nodal property, then we associate it with all its outgoing links.

Consider a GPS server employed in link $l \in E$ with rate $\overline{R}_l$ serving $I_l$ sessions. Each session $i$ is assigned a fixed real-valued positive parameter $\phi_i^l$, where $\{\phi_i^l\}_{1 \leq i \leq I_l}$ is called a GPS assignment. Let $S_{ij}^l(\tau, t)$ be the amount of session $i$’s traffic served during a time interval $[\tau, t]$. Then $\frac{S_{ij}^l(\tau, t)}{S_{ij}^l(\tau, t)} \geq \frac{\phi_i^l}{\phi_j^l}, j = 1, 2, \ldots, I_l$ for any session $i$ that is backlogged through the interval $[\tau, t]$. We note that a special case of the above is the Rate Proportional Processor Sharing (RPPS) GPS assign-
ment, where $\phi_i^j = \rho_i$, $1 \leq i \leq I$, and $\rho^j$ is the session upper rate.

As done in, e.g., [1, 8, 11, 12, 15], we map end-to-end delay guarantees into rate assignments. Namely, we assign the GPS parameters according to the required end-to-end delay. We assume that, for each session $i$, the GPS assignment $\phi_i^j$ is proportional to the required rate $r^i$, i.e., $\phi_i^j = r^i \rho^j$ and $\sum_{j=1}^I r^j < \bar{R}_i$. Obviously, with such an assignment, all sessions are locally stable [13] and we can follow the same network analysis as that of an RPPS-GPS network.

Denote by $R_i$ the maximal available rate which link $l$ can offer to a new connection. More formally, $R_i = \bar{R}_i - \sum_{j=1}^I r^j$, where $\bar{R}_i$ is the link’s service rate. When a new connection with a rate $r < R_i$ is established through link $l$, the value of $R_i$ becomes $R_i - r$. Let $R^1 \leq R^2 \leq \ldots \leq R^K$ be the different values of $R_i$, for all $l \in E$; clearly, $K \leq M$.

Following [8, 11, 12], we assume a source (“explicit”) QoS routing framework, in which link state information is exchanged and maintained up-to-date among network nodes for path computation. Routing decisions are based on the image of the network at the source node.

A session $i$ in the network is characterized by the following parameters:

- Source and destination nodes.
- Some stochastic bounds on the session’s burst.
- A traffic upper rate $\rho^i$, which constitutes the minimal bandwidth requirement.
- A maximum packet size $L^i$.
- A required end-to-end delay bound $D^i$.
- An upper bound on the delay-bound violation probability $q^i$.

A session should be routed through some path $p$ between the corresponding source and destination nodes. Let $H$ be the maximal possible number of hops in a path. We denote by $n(p)$ the number of hops (i.e., links) of a path $p$, and by $r(p)$ its maximal available rate, i.e., $r(p) = \min_{e \in p} R_e$. When a session $i$ is routed over a path $p$ with a reserved rate $r$ (where $r \leq r(p)$), the end-to-end delay, $D^i(p, r)$, is stochastically bounded. We also denote by $D^i(p)$ the minimal value of $D^i(p, r)$, i.e., $D^i(p) = D^i(p, r(p))$.

We assume that each session is associated with a certain probability $q^i$, which reflects its “sensitivity” to end-to-end delay fluctuations beyond the required delay. Accordingly, a path is said to be $q$-feasible if the end-to-end delay fluctuations beyond the required value conforms with the session’s sensitivity.

**Definition 1** The effective end-to-end delay $\bar{D}^i(p, q^i)$ of a path $p$, is the minimum delay bound, for which the delay bound violation probability is guaranteed to be at most $q^i$, i.e., $\Pr\{D^i(p) \geq \bar{D}^i(p, q^i)\} \leq q^i$.

**Definition 2** A path $p$ is $q$-feasible with respect to $D^i$ for session $i$ if the end-to-end delay tail distribution beyond the required delay $D^i$ is at most $q$, i.e., $\Pr\{D^i(p) \geq D^i\} \leq q$. Alternatively, a path $p$ is $q$-feasible if the effective delay $\bar{D}^i(p, q^i)$ of the path $p$ is at most the required delay $D^i$, i.e., $\bar{D}^i(p, q^i) \leq D^i$.

A session $i$ is $q$-feasible if it has a $q$-feasible path. Finally, a path with the minimal effective delay $\bar{D}^i(p, q^i)$ is termed $q$-quickest.

### 3. Stochastic Guarantees - EBB Traffic

In this section, we adopt the model introduced in [19] of Exponentially Bonded Burstiness (EBB) processes, defined as follows.

A stochastic process $A(t)$ is Exponentially Bonded (EB) with parameters $(\Lambda, \alpha)$, if for any $t$ and any $\sigma \geq 0$, the following bound applies: $\Pr\{A(t) \geq \sigma\} \leq \Lambda e^{-\alpha \sigma}$.

Let $A(t)$ be the instantaneous traffic rate. $A(t)$ has Exponentially Bonded Burstiness (EBB) with parameters $(\rho, \Lambda, \alpha)$, if for any $s, \tau$ and any $\sigma \geq 0$, the following upper bound, on the tail distribution of the traffic arriving during the time interval $[s, \tau]$, holds:

$\Pr\{\int_s^\tau A(t) \, dt \geq \rho (\tau - s) + \sigma\} \leq \Lambda e^{-\alpha \sigma}$.

First, we extend the results of [22] to a Packetized-GPS network, and, in addition, incorporate deterministic propagation delays. With the extended upper bound on the end-to-end delay tail distribution at hand, we study the corresponding QoS routing problem. We propose several routing schemes for identifying optimal path with respect to the following criteria: (i) minimizing the end-to-end delay tail distribution; (ii) minimizing a general cost function; (iii) finding a "quickest path". We then consider the application of a rate quantization method, which identifies a near-optimal solution with lower complexity.

#### 3.1. End-to-End Delay Tail Distribution

Consider a Rate Proportional Processor Sharing GPS network and EBB traffic. Assuming that packets are infinitely divisible (fluid model) and that propagation delays are negligible, the authors of [22] established an upper bound on the end-to-end delay tail distribution. In Proposition 1 we extend this result to Packetized traffic and non-negligible propagation delays.

**Proposition 1** Consider a session $i$ with EBB traffic in an RPPS GPS network. Let the traffic of session $i$ be routed over a path $p$ with a reserved rate $r^i$ (where $\rho^i <
Proposition 2. (i) Algorithm MDD correctly identifies the \( q \)-feasibility of the connection. (ii) Whenever the connection is \( q \)-feasible, the path \( p(\hat{k}) \), identified by the algorithm, achieves the minimal delay tail distribution upper bound \( \Pr(D, p(\hat{k})) \) among all \( q \)-feasible solutions. (iii) The algorithm’s complexity is \( O((N \log N + M) K) \).

3.2.2. Minimum Cost Path. Next, we consider the problem of finding a feasible path that optimizes some general cost function. Following [12], we consider a cost function \( C(r, p) \), which depends on the consumed rate \( r \) and the path \( p \). The only assumption that we make is that \( C(r, p) = C(r, n(p), D(p, r, q)) \) and that it is non-decreasing in each of its three arguments. In other words, the cost is a non-decreasing function of (i) the number of hops \( n(p) \), (ii) the consumed rate \( r \), and (iii) the effective end-to-end delay \( D(p, r, q) \) (where, \( \Pr(D(p, r, q)) \) the minimal upper bound on the end-to-end delay tail distribution, \( \Pr(D(p, r, q)) \).

Algorithm Minimum Cost (MC), specified in Fig. 2, identifies an optimal (i.e., minimum cost) path.

**Figure 1. Algorithm MDD**

1. For \( k \leftarrow 1 \) to \( K \):
   (a) Delete all links \( l \) with \( R_l < R^k \).
   (b) Find a path \( p(k) \) that is shortest with respect to the metric \( \{d_i\} \) through Dijkstra’s shortest path algorithm.
   (c) Taking \( r(p(k)) \leftarrow R^k \), compute \( \Pr(D, p(k)) \).

2. Choose the path \( p(\hat{k}) \) with the minimal upper bound \( \Pr(D, p(\hat{k})) \) among the \( K \) paths, \( p(k) 1 \leq k \leq K \).

3. If \( \Pr(D, p(\hat{k})) \leq q \) then \( p(\hat{k}) \) is \( q \)-feasible path, else there is no \( q \)-feasible path.

**Figure 2. Algorithm MC**

Proposition 3. Algorithm MC correctly identifies the \( q \)-feasibility of the connection. Whenever the connection is \( q \)-feasible, the path \( p(\hat{n}, \hat{k}) \) and rate \( r(\hat{n}, \hat{k}) \), identified by the algorithm, achieve the minimal cost among all \( q \)-feasible solutions. The algorithm’s complexity is \( O(MHK) \).
3.2.3. Quickest Path The third routing scheme seeks a “quickest path”, i.e., a path with a minimal effective end-to-end delay. The problem, then, is to find a path that minimizes the following expression:

\[
\hat{D}(p, q) = \begin{cases} 
\sum_{j \in p} d_j + \frac{n(p)L}{r(p)} - \frac{1}{\alpha r(p)} \ln \left( \frac{2}{\alpha r(p)} \right) - \ln \left( \frac{r(p)}{r(p)-\rho} \right) \\
+ \alpha r(p)(r(p)-\rho) \ln \left( \frac{r(p)}{r(p)-\rho} \right) - \frac{1}{\alpha r(p)} \ln (q) \\
+ \frac{1}{\alpha r(p)} \ln (\Lambda + 1)
\end{cases}
\]

Such a path can be identified by the execution of the MC algorithm with \( C(r, p) = \hat{D}(p, q) \). Alternatively, it can be identified through \( K \) executions of Dijkstra’s shortest path algorithm with respect to the metric \( \{ \frac{L}{R(j)} + d_l \} \) through Dijkstra’s shortest path algorithm.

\[
\text{Figure 3. Algorithm QP-RQ}
\]

1. \( R(0) \leftarrow R^1 \)
2. For \( j \leftarrow 0 \) to \( J \):
   a. If rate-class \( j \) is empty then skip to the next value of \( j \).
   b. Delete from the network all links whose rate-class is less than \( j \).
   c. Find the shortest path \( p(j) \) with respect to the metric \( \{ \frac{L}{R(j)} + d_l \} \) through Dijkstra’s shortest path algorithm.
   d. Compute \( \hat{D}(p(j), q) \).
   e. If \( R(j) < \rho (\Lambda + 1) \) then
      \[
      a_{j+1} \leftarrow \frac{\rho + (1+\varepsilon)^j (\Lambda + 1)(R^1 - \rho)}{(\Lambda + 1)(\Lambda + 1) + (1+\varepsilon)^j \Lambda}.
      \]
   else \( a_{j+1} \leftarrow \frac{(1+\varepsilon a_j)}{1+1+\varepsilon a_j}) \Lambda \).
   f. \( R(j+1) \leftarrow a_{j+1}R(j) \).
3. Among all paths \( p(j) \), choose a path \( p(\tilde{j}) \) with the minimal effective delay \( \hat{D}(p(\tilde{j}), q) \).

The algorithm’s complexity is

\[
O \left((N \log N + M) \min \left\{ \frac{1}{\varepsilon} \log \frac{\rho \Lambda (R^K - \rho)}{(R^1 - \rho)}, K \right\} \right).
\]

One can see that, with non-uniform quantization, the complexity is much lower, since now the complexity is relative to the logarithm of the expression \( \frac{\rho \Lambda (R^K - \rho)}{(R^1 - \rho)} \).

3.3. Simulation results

We now illustrate the advantage of the stochastic minimum cost algorithm through comparison with two standard QoS routing algorithms, namely, the “shortest-widest” and “widest-shortest” routing schemes [1]. We set the cost function to be the consumed rate, i.e., \( C(r, p) = n(p)q \). Our figure of merit is session acceptance probability, which is evaluated for various loads and network topologies. We assume that each session has EBB traffic with rate \( \rho = 1\)Mbps, \( \Lambda = 1 \) and \( \alpha = 2 \). Furthermore, we assume that each session requires a maximum end-to-end effective delay of 2msec and \( q = 10^{-4} \). We also assume that the session’s traffic is packetized and that the packet sizes are according to a trimodal distribution, namely, 60% of the packets being 44 bytes, 20% of the packets 552 bytes and the rest 1500 bytes. Following [11], we consider the two network topologies depicted in Fig. 4. Session requests arrive in sequentially. Once re-
sources are reserved within the network, they are held for the entire duration of the simulation experiment. We compare the following three routing algorithms: (i) Our algorithm minimum-rate, which identifies a $q$-feasible path with the minimum consumed rate. (ii) The “widest-shortest” algorithm [1], which, in our setting, identifies a $q$-feasible path with the minimum hop count. If there are several such paths, the one with the maximum residual bandwidth is selected. (iii) The “shortest-widest” algorithm [1], which, in our setting, identifies a $q$-feasible path with the maximum residual bandwidth. If there are several such paths, the one with the minimum hop count is selected.

![Networks topologies](image)

**Figure 4. Networks topologies**

The blocking rate is evenly distributed (source and destination nodes requests) for the two network topologies when the traffic is identified by the minimum residual bandwidth. If there are several such paths, the one with the minimum hop count is selected. (iii) The “shortest-widest” algorithm [1], which, in our setting, identifies a $q$-feasible path with the maximum residual bandwidth. If there are several such paths, the one with the minimum hop count is selected.

![Flow request blocking probability](image)

**Figure 5. Flow request blocking probability**

Fig. 5(a) and Fig. 5(b) present the blocking probability as a function of the load (i.e., number of session requests) for the two network topologies when the traffic is evenly distributed (source and destination nodes are randomly selected). Note that the blocking rate is evaluated as the average number of rejected sessions divided by the number of session requests. Fig. 5(c) and Fig. 5(d) show the results for an uneven load, where most of the traffic (90%) is between “East” and “West” (the source/destination node is randomly selected from the East/West nodes, respectively). In practice, blocking rates higher than some 10% may be prohibitive. Hence, focusing on the load region for which the blocking rate is lower than 10%, our minimum-rate algorithm outperforms both the widest-shortest as well as the shortest-widest algorithms in all considered scenarios. Furthermore, considering all traffic loads (i.e., also those resulting with block rates of more than 10%), our minimum-rate algorithm achieves good network utilization both for evenly as well as unevenly distributed traffic; on the other hand, the shortest-widest and widest-shortest algorithms achieve bad network utilization for evenly/unevenly distributed traffic, respectively.

### 4. Stochastic Guarantees - SBB Traffic

We consider a more general source traffic model, of Stochastically Bounded Burstiness (SBB) processes, whose burstiness is stochastically bounded by a general decreasing function [17]. The SBB approach is based on a generalization of the EBB network calculus, where only exponentially decaying bounding functions were considered. This approach has two major advantages: (i) it applies to a larger class of input processes, and (ii) it provides much better bounds for common models of real-time traffic. [17] formulated the SBB calculus for an isolated network element and considered the stability of a feed-forward network. We proceed to present the formal definition.

A stochastic process, $A(t)$, is Stochastically Bounded ($SB$) with bounding function $f(\sigma)$ if: (i) $f(\sigma) \in \Gamma$, (ii) $R \{ A(t) \leq \sigma \} \leq f(\sigma)$ for all $\sigma \geq 0$ and all $t \geq 0$, where $\Gamma$ represents the set of all the functions $f(\sigma)$ such that, for any order $n$, the multiple integral $(f^{\infty})^{n}(t)$ is bounded for any $\sigma \geq 0$.

The rate of a continuous traffic stream $A(t)$ has Stochastically Bounded Burstiness (SBB), with upper rate $\rho$ and bounding function $f(\sigma)$, if: (i) $f(\sigma) \in \Gamma$, (ii) $R \{ A(t) dt \geq \rho (\tau-s) + \sigma \} \leq f(\sigma)$ for all $\sigma \geq 0$ and all $0 \leq s \leq \tau$.

We consider SBB traffic entering an RPPS PGPS network, and establish bounds on the end-to-end backlog and delay tail distribution. We then consider the related routing problem; due to the complexity of the bounds, we focus on the special case in which the bounding function is the sum of two exponents, and
provide a near-optimal routing algorithm of low complexity.

4.1. End-to-End Delay Tail Distribution

In the following proposition we establish an upper bound on the end-to-end delay tail distribution in an RPPS PGPS network.

**Proposition 5** For every session $i$ with SBB traffic in an RPPS PGPS network, for any $\xi > 0$ and $D > 0$:

$$
\Pr \left\{ D^i (p) \geq D \right\} \leq f \left( \left( \eta^i (p) - \rho^i \right)^+ \right) + \frac{1}{(r(p) - \rho^i) \xi} \int_{\eta^i (p) - \rho^i}^{\infty} f (u) du, \tag{3}
$$

where, $\eta^i (p) \triangleq \rho (p) \left( D - \sum_{l \in p} d_l \right) - n (p) L$, and the notation $(\cdot)^+$ denotes the operation $\max (\cdot, 0)$. ■

4.2. Special Case: Sum of Exponents

As a special case of the SBB model, consider a bounding function that is the sum of two exponents. For this case, we can provide better bounds than those obtained for the EBB model (i.e., a single exponent); at the same time, these bounds have a simple closed form, just as in the EBB case.

Let the bounding function be $\Lambda e^{-\alpha \sigma} + Be^{-\beta \sigma}$, i.e., for all $\sigma \geq 0$, $0 \leq s \leq \tau$, $\Pr \{ A (s, \tau) \geq \rho (\tau - s) + \sigma \} \leq \Lambda e^{-\alpha \sigma} + Be^{-\beta \sigma}$. According to proposition 5, in an RPPS PGPS network, for every session $i$ with SBB traffic and a bounding function $f (\sigma) = \Lambda e^{-\alpha \sigma} + Be^{-\beta \sigma}$ and for any $\xi > 0$ and $D > 0$:

$$
\Pr \left\{ D (p) \geq D \right\} \leq \frac{1}{\alpha (r(p) - \rho) \xi} \Lambda e^{-\alpha (\eta (p) - \rho \xi)} + \frac{1}{\beta (r(p) - \rho) \xi} Be^{-\beta (\eta (p) - \rho \xi)}, \tag{4}
$$

where, $\eta (p) \triangleq \rho (p) \left( D - \sum_{l \in p} d_l \right) - n (p) L$.

Denote the upper bound on end-to-end delay tail distribution, given in (4), as $\Pr (D, p)$.

4.2.1. Routing Algorithms

We consider the problem of finding a path with the minimal bound on the end-to-end delay tail distribution. Although the bound (4) is quite complex, it is easy to verify that it is still the same, relatively simple, metric (for a given $r$), namely $\left\{ \frac{D}{r} + d \right\}$, that characterizes the path with respect to the end-to-end delay tail distribution bound. Thus, an optimal path can be identified through $K$ executions of Dijkstra's shortest path algorithm with respect to the metric $\left\{ \frac{D}{r} + d \right\}$. To achieve lower complexity, one can recur to a rate-quantized, near-optimal solution, such as specified in Fig. 6.

- $R (0) \leftarrow R^1$
- For $j \leftarrow 0$ to $J$:
  - (a) If rate-class $j$ is empty then skip to the next value of $j$.
  - (b) Delete from the network all links whose rate-class is less than $j$.
  - (c) Find the shortest path $p (j)$ with respect to the metric $\left\{ \frac{D}{R (j)} + d \right\}$ through Dijkstra's algorithm.
  - (d) Compute $Pr (D, p)$.
  - (e) $a_{j+1} \leftarrow \frac{1}{\rho + (1+\epsilon) \frac{\beta \sigma}{\rho (1+\epsilon) \sigma}} (R^1 - \rho)^{1+\epsilon},$ $\frac{1+\epsilon}{\rho + (1+\epsilon) \sigma}$ $(R^1 - \rho)$.
  - (f) $R (j + 1) \leftarrow a_{j+1}, R (j)$

3. Among all paths $p (j)$, choose a path $\tilde{p}$ with the minimal end-to-end delay tail distribution bound $\Pr (D, p)$.

**Figure 6. Algorithm MDD-RQ**

**Proposition 6** The path $\tilde{p}$ identified by Algorithm MDD-RQ, constitutes an $\varepsilon$-optimal solution, i.e.: $\Pr ((1 + \varepsilon) D, \tilde{p}) \leq \Pr (D, p^\star)$. The algorithm’s complexity is $O \left( (N \log N + M) \min \left\{ \frac{1}{\varepsilon} \log \left( \frac{R^K - \varepsilon}{\rho^* - \rho} \right), K \right\} \right)$ ■

5. Conclusion

This study contributes to two major subjects within the area of QoS provision. First, it considers QoS routing schemes that are designed to operate in conjunction with rate-based service disciplines. While previous studies (e.g., [8, 11, 12]) exclusively dealt with (deterministically) burstiness constrained (BC) traffic and deterministic guarantees, in this study we investigated the problem within the realm of stochastically bounded burstiness (SBB) and stochastic guarantees.

The second contribution of this study was in fact a prerequisite for the first. Namely, in order to establish appropriate routing schemes, we needed to have at hand end-to-end delay bounds for networks of packetized servers and links with non-negligible propagation delays. Since previous work on stochastic (EBB, SBB) settings have been carried on more limited models (at times, on a single, isolated server), we had to make the required extensions. As a result, the present study is the first to provide end-to-end bounds in a “full” network model, for the settings of EBB and SBB traffic.

The new bounds have a much more complex structure than the deterministic bound of the “basic” BC setting. Moreover, the way they should be employed within a corresponding routing scheme is
not as straightforward as in the basic setting. Yet, once the right observations are made, the complexity of the resulting QoS routing scheme is typically not higher than in the basic setting. Special care is often required also when attempting to adopt the rate quantization approach of [12], e.g., as demonstrated by the non-uniform quantization method applied in algorithm QP-RQ. After having established the routing schemes, we tested them by means of simulation examples. Here, we demonstrated that our MC routing algorithm achieves better network utilization (in terms of blocking probability) than the standard shortest-widest and widest-shortest routing algorithms. In addition, we demonstrated in [2] that our MDD routing algorithm correctly identifies a “stochastically”-feasible path, whereas a corresponding deterministic routing algorithm may identify a false path that is not “stochastically”-feasible. It is important to note that, while our algorithms rely on somewhat complex analysis, their computational complexity is polynomial and quite comparable to that of simple shortest path algorithms as those employed by standard routing protocols.

Last, we outline several possible directions for future research. Throughout the analysis, we have focused on RPPS PGPS schedulers. However, many other rate-based scheduling disciplines, which are non-rate-proportional or non-GPS, have been established and explored. Thus, a possible area for future research is the establishment of QoS routing schemes for such disciplines. Another, more immediate direction is to extend the current routing schemes in order to consider additional optimization criteria.

References


