Adaptive Proportional Routing: A Localized QoS Routing Approach

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***Abstract*—Most of the QoS routing schemes proposed so far require periodic exchange of QoS state information among routers, imposing both communication overhead on the network and processing overhead on core routers. Furthermore, stale QoS state information causes the performance of these QoS routing schemes to degrade drastically. In order to circumvent these problems, we focus on *localized* QoS routing schemes where the edge routers make routing decisions using only local information and thus reducing the overhead at core routers. We first describe *virtual capacity based routing* (vcr), a theoretical scheme based on the notion of *virtual capacity* of a route. We then propose *proportional sticky routing*, an easily realizable approximation of vcr and analyze its performance. We demonstrate through extensive simulations that adaptive proportional routing is indeed a viable alternative to the global QoS routing approach.**

***Index Terms*—Localized proportional routing, quality-of-service routing.**

I. INTRODUCTION

QUALITY-OF-SERVICE (QoS) routing is concerned with the problem of how to select a path for a flow such that the flow's QoS requirements such as bandwidth or delay are likely to be met. In order to make judicious choices in path selection, it is imperative that we have some knowledge of the global network QoS state, e.g., the traffic load distribution in the network. In the design of any QoS routing scheme, we must therefore address the following two key questions: 1) how to obtain some knowledge of the global network state and 2) given this knowledge, how to select a path for a flow. Solutions to these questions affect the performance and cost tradeoffs in QoS routing.

The majority of QoS routing schemes [1], [5], [8], [16], [28], [31], [32] proposed so far require the periodic exchange of link QoS state information among network routers to obtain a global view of the network QoS state. This approach to QoS routing is thus referred to as the global QoS routing approach. Because network resource availability changes with each flow arrival and departure, maintaining accurate network QoS state requires frequent information exchanges among the network nodes (routers). The prohibitive communication and processing overheads entailed by such frequent QoS state updates precludes the possibility of always providing each node with an accurate view of the current network QoS state. Consequently, the network QoS state information acquired at a source node can quickly become out-of-date when the QoS state update interval is large relative to the flow dynamics. Under these circumstances, exchanging QoS state information among network nodes is superfluous. Furthermore, path selection using algorithms that treat stale QoS state information as accurate does not seem to be judicious. In addition, the global view of the network QoS state may lead to the so-called synchronization problem: after one QoS state update, many source nodes choose paths through links with high perceived available bandwidth, therefore causing overutilization of these links. After the next QoS state update, the source nodes would avoid the paths through these links, resulting in their underutilization. This oscillating behavior can have severe impact on the system performance, when the QoS state update interval is large. Due to these drawbacks, it has been shown that, when the QoS update interval is large relative to the flow dynamics, the performance of global QoS routing schemes degrades significantly [1], [19], [28]. Though there have been some remedial solutions proposed in [8], [1], and [2] to deal with the inaccuracy at a source node, the fundamental problem is still not completely eliminated.

As a viable alternative to the global QoS routing schemes, in [19], [20] we have proposed a localized approach to QoS routing. Under this approach, no global QoS state information exchange among network nodes is needed. Instead, source nodes infer the network QoS state based on flow blocking statistics collected locally, and perform flow routing using this localized view of the network QoS state. The proposed localized QoS routing approach has several advantages. First of all, without the need for global information exchange, the communication overhead involved is minimal. Second, core routers (i.e., non-source routers) do not need to keep and update any QoS state database necessary for global QoS routing, thereby reducing the processing and memory overhead at core routers. Last, but not least, the localized QoS routing approach does not require any modification or extension to existing routing protocols such as OSPF. Only source routers need to add a QoS routing enhancement to the existing routing module. This makes localized QoS routing schemes readily deployable with relatively low cost.

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The fundamental question in the design of a localized QoS routing scheme is how to select paths based solely on a local view of the network QoS state so as to minimize the chance of a flow being blocked as well as to maximize the overall system resource utilization. The problem of path selection in localized QoS routing is complicated by many factors. For example, due to complex network topology, paths between many source–destination pairs may share links whose capacity and load are unknown to the sources. Furthermore, the network load can fluctuate dynamically, which can make a previously unloaded link suddenly overloaded. In addition, path selection decision made by one source may affect the decision of another source.

To effectively address these difficulties, we study a novel adaptive proportional routing approach for designing localized QoS routing schemes. Here we assume that the path-level statistics, such as the number of flows blocked, is the only available QoS state information at a source. Based on these statistics, adaptive proportional routing attempts to proportionally distribute the load from a source to a destination among multiple paths according to their perceived quality (e.g., observed flow blocking probability). In other words, adaptive proportional routing exploits the inherent randomness in path selection by proportioning flows among multiple paths. This is fundamentally different from the conventional, deterministic path selection algorithms used in global routing schemes, which always choose the "best" feasible path to route a flow. As a result, adaptive proportional routing effectively avoids the synchronization problem associated with global QoS routing schemes.

There are three major objectives in our investigation of adaptive proportional routing: adaptivity, stability, and simplicity. With only a localized view of the network QoS state, it is important to adjust flow proportions along various paths adaptively in response to the dynamically changing network load. Stability is essential to ensure efficient system resource utilization and thus the overall flow throughput. Lastly, we are interested in employing simple local rules and strategies at individual sources to achieve adaptivity and to ensure stability.

Toward these goals, we present a theoretical framework for studying adaptive proportional routing. Using Erlang's Loss Formula, we introduce the notion of virtual capacity which provides a mathematical framework to model multiple paths between a source and a destination, as well as to compute flow proportions based on locally observed flow blocking probabilities. We also introduce a self-refrained alternative routing method to deal with the potential "knock-on" effect in QoS routing. By incorporating this self-refrained alternative routing method into the virtual capacity model, we design a theoretical adaptive proportional routing scheme which allows source nodes in a network to adaptively adjust their flow proportions based solely on locally observed flow blocking statistics. Through numerical examples, we demonstrate the desired self-adaptivity of this theoretical adaptive proportional routing scheme in achieving an eventual equilibrium system state. As a simple and practical implementation of the theoretical scheme, we present a scheme, proportional sticky routing (psr), which preserves the self-adaptivity of the theoretical scheme while avoiding its computational overhead. Finally, comparison of the psr scheme with the well-studied global QoS routing scheme, the widest shortest path (wsp) scheme, is made using simulations. These simulation results demonstrate that with its low overhead and comparable performance, a simple and easy-to-implement localized QoS routing scheme such as psr provides a viable alternative to a global QoS routing scheme such as wsp.

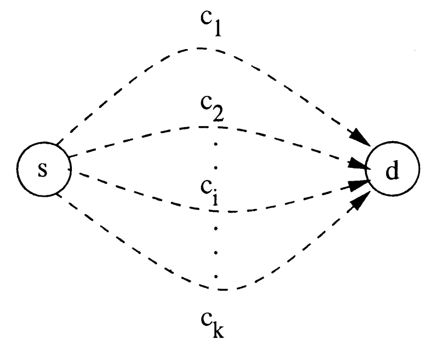


Fig. 1. Disjoint paths between a source–destination pair.

The remainder of the paper is organized as follows. Section II presents a theoretical framework for studying adaptive proportional routing. Section III describes the psr scheme, and simulation results are shown in Section IV. In Section V, the related work is presented. Section VI concludes the paper.

II. Adaptive Proportional Routing

In all the QoS routing models we consider in this paper, we assume that source routing is used. More specifically, we assume that network topology information is available to all source nodes (e.g., via the OSPF protocol), and one or multiple explicit-routed paths are set up *a priori* for each source and destination pair using, e.g., MPLS [27]. Flows arriving at a source to a destination are routed along one of the explicit-routed paths (hereafter referred to as the candidate paths). In this section, we first describe how to proportion the load among multiple candidate paths when they are all mutually disjoint. The notion of virtual capacity of a path is then introduced to deal with sharing of links among different paths. A self-refrained alternative routing method is proposed to address the potential "knock-on" effect due to alternative routing. We then present a theoretical adaptive proportional routing scheme that incorporates this localized trunk reservation method into the virtual capacity model.

A. An Idealized Proportional Routing Model

Consider a simple fork topology shown in Fig. 1, where a source s and a destination d are connected by k disjoint paths $r_1, r_2, \ldots, r_k$. Each path r_i has a (bottleneck) capacity of c_i units of bandwidth and is assumed to be known to the source s. Suppose flows arrive at the source s at an average rate λ, and the average flow holding time is $1/\mu$. Throughout this section, we assume that flow arrivals are Poisson and flow holding times are exponentially distributed. For simplicity, we also assume that each flow consumes one unit of bandwidth.[1] In other

[1]The models presented in this paper can be extended to the case where flows have different bandwidth requirements using the extended Erlang loss formula [14], [25]. In Section IV, we conduct a simulation study of our localized QoS routing scheme using flows with heterogeneous bandwidth requirements.

words, path r_i can accommodate c_i flows at any time. Without precise knowledge of the QoS state of a path (i.e., the available bandwidth of the path), a flow routed along the path has a certain probability of being blocked. Therefore, the question is how to route flows along these k paths so that the overall blocking probability is minimized. This problem can be formulated using the classic Erlang's loss formula as follows.

Suppose that, on the average, the proportion of flows routed along path r_i is α_i, where $i = 1, 2, \ldots, k$, and $\sum_{i=1}^{k} \alpha_i = 1$. Then the blocking probability b_i at path r_i is given by

$$b_i = E(\nu_i, c_i) = \frac{\frac{{\nu_i}^{c_i}}{c_i!}}{\sum\limits_{n=0}^{c_i} \frac{\nu_i^n}{n!}}$$

where $\nu_i = \alpha_i(\lambda/\mu)$ is referred to as the (average) load on path i. The total load on the system is denoted by $\nu = \sum_{i=1}^{k} \nu_i = \lambda/\mu$. To minimize the overall blocking probability, the optimal routing strategy (in the absence of precise knowledge of QoS state of each path) is therefore to route α_i^* proportion of flows along path r_i, $i = 1, 2, \ldots, k$, such that $\sum \alpha_i^* = 1$ and $\sum \nu\alpha_i^* b_i^*$ is minimized. This optimal proportional routing (opr) strategy can be implemented, for example, by routing flows to path r_i with probability α_i^*.

Given the total load ν and the path capacities c_i's, the optimal proportions α_i^*'s can be computed using an iterative search technique which is generally quite complex to implement in practice. To circumvent this problem, we consider two alternative strategies for flow proportioning: equalization of blocking probabilities (ebp) and equalization of blocking rates (ebr). The objective of the ebp strategy is to find a set of proportions $\{\tilde{\alpha}_1, \tilde{\alpha}_2, \ldots, \tilde{\alpha}_k\}$ such that flow blocking probabilities of all the paths are equalized, i.e., $\tilde{b}_1 = \tilde{b}_2 = \cdots = \tilde{b}_k$, where $\tilde{b}_i$ is the flow blocking probability of path r_i, and is given by $E(\tilde{\alpha}_i\nu, c_i)$. The intuition behind ebp strategy is that if blocking probability b_i of a path r_i is greater than blocking probability b_j of a path r_j ($b_i > b_j$), then we can minimize the overall blocking probability by shifting some load from r_i to r_j. This increases b_j and decreases b_i and equilibrium state is reached when they are equal. On the other hand, the objective of the ebr strategy is to find a set of proportions $\{\hat{\alpha}_1, \hat{\alpha}_2, \ldots, \hat{\alpha}_k\}$ such that flow blocking rates of all the paths are equalized, i.e., $\hat{\alpha}_1\hat{b}_1 = \hat{\alpha}_2\hat{b}_2 = \cdots = \hat{\alpha}_k\hat{b}_k$, where $\hat{b}_i$ is the flow blocking probability of path r_i, and is given by $E(\hat{\alpha}_i\nu, c_i)$. The rationale behind ebr strategy is to assign a proportion α_i to a path r_i such that α_i is inversely proportional to blocking probability b_i along path r_i, i.e., $\alpha_i \propto 1/b_i$. This results in equalization of blocking rates.

Unlike the optimal proportions, α_i^*'s, the proportions of ebp, $\tilde{\alpha}_i$s, and those of ebr, $\hat{\alpha}_i$s, can be computed using a simple iterative procedure starting with any arbitrary proportions. For example, consider the ebp strategy. Suppose we start with an initial set of proportions $\alpha_1^{(0)}, \alpha_2^{(0)}, \cdots, \alpha_k^{(0)}$. Let the corresponding blocking probabilities be $b_1^{(0)}, b_2^{(0)}, \cdots, b_k^{(0)}$, where $b_i^{(0)} = E(\alpha_i^{(0)}\nu, c_i)$. If $b_i^{(0)}$s are all equal, then $\alpha_i^{(0)}$'s are the desired proportions. Otherwise, we use the mean blocking probability over all the paths $\overline{b}^{(0)} = \sum b_i^{(0)}/k$ as the target blocking probability for each path and obtain a new set of proportions $\alpha_i^{(1)}$'s. The new proportions $\alpha_i^{(1)}$'s are computed from the Erlang's loss formula as follows: for $i = 1, 2, \ldots, k$, find the new load on path r_i, $\nu_i^{(1)}$, such that $\overline{b}^{(0)} = E(\nu^{(1)_i}, c_i)$. Then

$$\alpha_i^{(1)} = \frac{\nu_i^{(1)}}{\sum\limits_{j=1}^{k} \nu_j^{(1)}}.$$

This procedure is repeated iteratively until we obtain a set of proportions such that the corresponding blocking probabilities are equal. Since for a fixed c_i the blocking probability b_i is an increasing function of its load $\alpha_i\nu$, it can be shown that the above iterative procedure will always converge. In the case of the ebr strategy, a similar iterative procedure can be used to obtain a set of proportions which equalize the blocking rates of all the paths.

TABLE I
COMPARISON OF ebp, ebr, AND opr

Scenario		*ebp*	*ebr*	*opr*
$c_1 = 20, c_2 = 20, \nu = 27$	*obp*	2.36	2.36	2.36
$c_1 = 10, c_2 = 20, \nu = 22$	α_1	0.292	0.327	0.307
	α_2	0.708	0.673	0.693
	b_1	5.68	8.68	6.87
	b_2	5.62	4.22	5.01
	obp	5.64	5.68	5.58
$c_1 = 10, c_2 = 20, \nu = 18$	α_1	0.277	0.307	0.290
	α_2	0.723	0.693	0.710
	b_1	1.82	3.01	2.29
	b_2	1.82	1.33	1.59
	obp	1.82	1.84	1.80

Table I shows the convergence points of the ebp, ebr, and opr strategies for a source–destination pair with two disjoint paths under different scenarios. As expected, when the capacities are equal all three strategies assign equal proportions for the two paths and yield same overall blocking probability. However, when the capacities are not equal, the equilibrium proportions for the two paths under the three strategies are different. It can be observed, however, the overall blocking probabilities under the ebp and ebr strategies are both quite close to that of the optimal strategy. Since it is generally computationally cumbersome to find the optimal equilibrium proportions, in this paper we explore the two simple strategies, ebp and ebr, for adaptive proportional routing.

B. Virtual Capacity Model

In the idealized proportional routing model described above, we have assumed that all paths between a source and a destination are disjoint and their bottleneck link capacities are known. In practice, however, paths between a source and a destination have shared links. These paths may also share links with paths between other source–destination pairs. Furthermore, as traffic patterns across a network change, the bottleneck link of a path and its (perceived) capacity may also change. In order to address these issues, we introduce the notion of virtual capacity (vc) of a path.

Consider a source–destination pair. We model each path between them as one direct virtual link with a certain amount of capacity, referred to as the virtual capacity of the path. This virtual capacity is a function of the load offered by the source along the path and the corresponding blocking probability observed by the source. Formally, consider a path r between a source and a destination. Suppose a load of ν_r is offered by the source along the path, and the corresponding blocking probability observed by the source is b_r. Then the virtual capacity of the path, denoted by vc_r, is given by $vc_r = E_{vc}^{-1}(\nu_r, b_r)$, where $E_{vc}^{-1}(\nu_r, b_r)$ denotes the inverse function of the Erlang's loss formula[2] with respect to the capacity and is given by

$$vc_r = E_{vc}^{-1}(\nu_r, b_r) := \min\{c \geq 0: E(\nu_r, c) \leq b_r\}.$$

Based on this notion of virtual capacity, we can model paths between a source and a destination as if they were all disjoint and had bottleneck capacities equal to their virtual capacities, as in the idealized proportional routing model. Unlike the idealized proportional routing model, however, the virtual capacity of a path is not fixed, but is a function of its offered load and the corresponding blocking probability. Since the virtual capacity of a path depends only on local statistics at a source (i.e., the offered load by a source and the corresponding blocking probability observed by the source), flow proportioning based on virtual capacities of paths does not require any global QoS state information exchange.

A key feature of virtual capacity model is self-adaptivity: proportions of flows along different paths between a source and a destination will be adjusted based on the observed blocking probabilities of those paths. From the definition of virtual capacity, we observe that for two paths with the same offered load, the path with higher observed blocking probability has lower virtual capacity. Therefore, if we are to equalize the observed blocking probabilities or blocking rates along these two paths, more flows should be routed to the path with lower observed blocking probability (and higher virtual capacity). The new proportions for these two paths can be computed based on their virtual capacities, as in the idealized proportional routing model.

We illustrate the self-adaptivity of the virtual capacity model through an example. Consider the kite topology shown in Fig. 2(a), where two sources, s_1 and s_2, have two paths each to destination d, and two of the paths share a common link $(4 \rightarrow 6)$. The links with labels are the bottleneck links of the network, where $c_1 = c_2 = c_3 = 20$, and all the other links can be viewed to have infinite capacities (i.e., flows are never blocked on these links). Let r_1^1, r_2^1 denote paths $1 \rightarrow 3 \rightarrow 6$ and $1 \rightarrow 4 \rightarrow 6$, respectively, and r_1^2, r_2^2 denote the paths $2 \rightarrow 5 \rightarrow 6$ and $2 \rightarrow 4 \rightarrow 6$, respectively. The virtual capacity views of the two source–destination pairs are shown in Fig. 2(b), where the paths r_2^1 and r_2^2 appear to each source as if they were disjoint with capacities vc_2^1 and vc_2^2, respectively. Note that, if a path does not share links with any other path, its virtual capacity is the same as its actual bottleneck link capacity.

First, consider the scenario where a load of 22 is offered at each of the sources. Suppose initially each source proportions flows equally between its two paths, i.e., $\nu_j^i = 11$, $i, j = 1, 2$. The blocking probabilities observed on paths r_1^1, r_2^1, r_2^2, and r_1^2 are $b_1^1 = 0.0046$, $b_2^1 = 0.2090$, $b_2^2 = 0.2090$, and $b_1^2 = 0.0046$, respectively, resulting in an overall blocking probability of 0.1068. The corresponding virtual capacities are $vc_2^1 = 12$, and $vc_2^2 = 12$. In particular, we see that the shared link of paths r_2^1 and r_2^2 is treated by each source as an exclusive link with capacity 12. For both sources, since the blocking probability of path r_2^i is much higher than path r_1^i, more flows will be proportioned to path r_1^i, as it has a larger virtual capacity. The new proportions can be computed based on the virtual capacities of the paths, using either the ebp strategy or the ebr strategy. For example, using the ebp strategy, the adaptation process for source s_1 is shown on the left side (scenario I) of Fig. 3(a), where we see that after a few iterations the flow blocking probabilities of both paths r_1^1 $(1 \rightarrow 3 \rightarrow 6)$ and r_2^2 $(1 \rightarrow 4 \rightarrow 6)$ are equalized at around 0.04. Fig. 3(b) shows the corresponding proportions of flows routed along these two paths during this adaptation process, where we see that source s_1 backs off from the path (r_2^1) with the shared bottleneck link $4 \rightarrow 6$, and directs more flows to the other path (r_1^1). The resulting flow proportions for path r_1^1 and r_2^1 at the equilibrium state are, respectively, 0.667 and 0.333. Due to the symmetry in this scenario, source s_2 behaves in exactly the same manner and achieves the same equilibrium flow proportions for its two paths r_1^2 and r_2^2. Similarly, if we employ the ebr strategy, both sources will also gradually back off from the paths with the shared bottleneck link and arrive at an equilibrium state.

Now consider the scenario where, after the above equilibrium state is achieved, the offered load at s_1 increases from 22 to 25 whereas the offered load at s_2 decreases from 22 to 15. Given the new load at both sources, routing flows along the paths using the old equilibrium proportions no longer results in an equilibrium state. In particular, source s_1 sees a blocking probability of $b_1^1 = 0.0784$ on path r_1^1 and a blocking probability of $b_2^1 = 0.0216$ on path r_2^1. On the other hand, source s_2 sees a blocking probability of $b_1^2 = 0.0018$ on path r_1^2 and a blocking probability of $b_2^2 = 0.0216$ on path r_2^2. Hence, in an effort to equalize the blocking probabilities on both paths, s_1 will direct more flows to path r_2^1

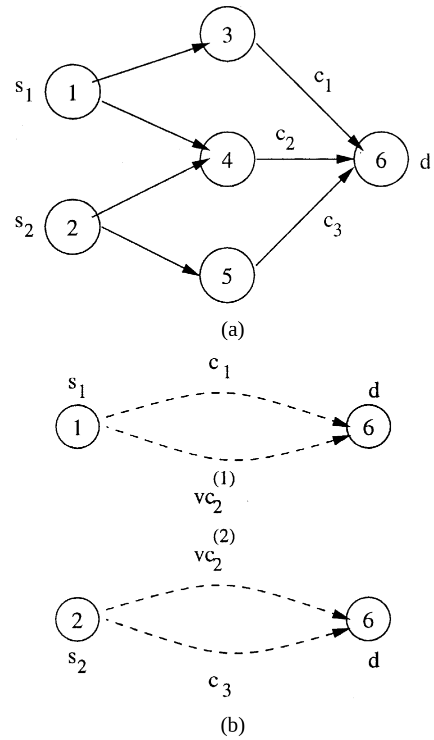


Fig. 2. Views. (a) Physical. (b) Virtual.

[2]Note that $E_{vc}^{-1}(\nu_r, b_r)$ defined above is an integer-valued function. A continuous version of the Erlang's loss formula and its inverse functions can be defined [6] and used instead. For more details, the interested reader is referred to [21].

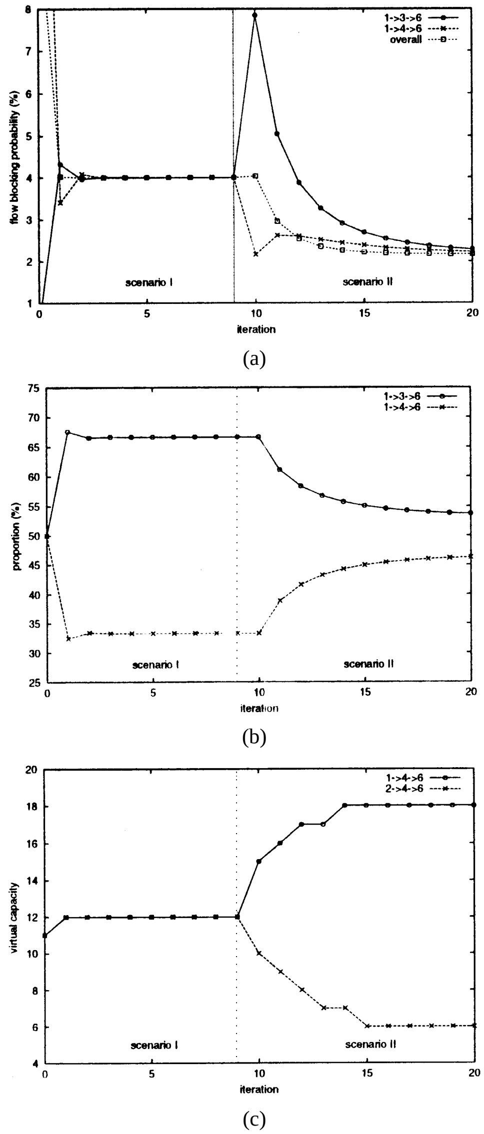


Fig. 3. Adaptation process of ebp. (a) Changes in blocking probabilities. (b) Changes in proportions. (c) Changes in virtual capacities.

and s_2 will direct more flows to path r_1^2. The new adaptation process is shown on the right side (scenario II, starting with iteration 10) of Fig. 3(a). From the figure we see that, as source s_1 directs more flows to path r_2^1, the observed blocking probability on path r_2^1 gradually increases while the observed blocking probability on path r_1^1 gradually decreases. These two blocking probabilities are eventually equalized at around 0.022. The proportions of flows routed along the two paths by source s_1 during this adaptation process are shown in Fig. 3(b).

It is interesting to note that each source adapts to the load changes not with any global objective but with a local objective of equalizing blocking probabilities or rates among all paths to a given destination. This in turn results in an overall near-optimal stable system performance. For example, in scenario I, both source s_1 and source s_2 have an equal capacity share on the bottleneck link $4 \rightarrow 6$, each with a virtual capacity of 12. But as the load changes at each source, source s_1 starts routing more flows to path r_2^1, whereas source s_2 starts backing off from the path r_2^2, thereby allowing s_1 to grab more capacity share on the bottleneck link. The changes in the virtual capacity of the shared link seen by each source are shown in Fig. 3(c). At the end, source s_1 has a virtual capacity of 18 from the shared bottleneck link, while source s_3 has a virtual capacity of 6. Due to this change in capacity shares, the blocking probability observed by source s_1 is reduced from 0.0595 at the onset of load change to 0.0225 in the end while that of s_2 goes up from 0.0084 to 0.0202. However, as a consequence of these self-adaptations at the two sources, the overall system blocking probability is reduced from 0.0404 to 0.022.

C. Self-Refrained Alternative Routing

In the virtual capacity model, all paths between a source and a destination are treated equally. Since an admitted flow consumes bandwidth and buffer resources at all the links along a path, clearly path length is also an important factor that we must take into consideration. There is a fundamental trade-off between minimizing the resource usage by choosing shorter paths and balancing the network load by using lightly loaded longer paths. As a general principle, it is preferable to route a flow along minhop (i.e., shortest) paths than paths of longer length (also referred to as alternative paths).[3] Preferring minhop paths and discriminating against alternative paths, not only reduces overall resource usage but also limits so-called "knock-on" effect [10], [11], thereby ensuring stability of the whole system.

The knock-on effect refers to the phenomenon where using alternative paths by some sources forces other sources whose minhop paths share links with these alternative paths to also use alternative paths. This cascading effect can cause a drastic reduction in the overall throughput of the network. In order to deal with the knock-on effect, trunk reservation [11] is employed where a certain amount of bandwidth on a link is reserved for minhop paths only. With trunk reservation, a flow may be rejected even if sufficient resources are available to accommodate it. A flow along a path longer than its minhop path is admitted only if the available bandwidth even after admitting this flow is greater than the amount of trunk reserved. Trunk reservation provides a simple and yet effective mechanism to control the knock-on effect. However, it requires that core routers figure out whether a setup request for a flow is sent along its minhop path or not. This certainly introduces undesirable burden on core routers. To avoid this, we propose a self-refrained alternative routing method, which when employed at a source provides an adaptive way to discriminate against "bad" alternative paths without explicit trunk reservation.

Consider a source–destination pair. Suppose there are $k^{\min}$ number of minhop paths between this source–destination pair, and let $R^{\min}$ denote the set of these minhop paths. The set of alternative paths is denoted by R^{alt}. Thus the set of all candidate paths $R = R^{\min} \cup R^{alt}$. The basic idea behind the self-refrained alternative routing method is to ensure that an alternative path is used to route flows between the source–destination pair only if it has a "better quality" (measured in flow blocking probability) than any of the minhop paths. Formally, for a path $r \in R^{\min}$, let b_r denote the observed flow blocking probability on path r. The minimum flow blocking probability of all the minhop paths,

[3]Although the virtual capacity model does not explicitly take path length into account, it does tend to discriminate against longer paths implicitly, as longer paths are likely to have a higher blocking probability in practice.

$b^* = \min_{r \in R^{\min}} b_r$, is used as the reference in deciding a target flow blocking probability for alternative paths. The target flow blocking for alternative paths is set to ψb^*, where ψ is a configurable parameter to limit the knock-on effect under system overloads. An alternative path $r' \in R^{alt}$ is selected to route flows only if it can attain the target flow blocking probability. In other words, its observed flow blocking probability $b_{r'}$ is less than or equal to ψb^*.

This self-refrained alternative routing method has several attractive features. By using b^* as the reference in determining a target flow blocking probability for alternative paths, it dynamically controls the extent of alternative routing according to both the load at the source and the overall system load. For example, if both the load at the source and the overall system load is light, the use of alternative paths will be kept at a minimum. However, if the load at the source is heavy but the overall system load is light, more alternative routes will be used by the source. Furthermore, by using only those alternative paths whose observed blocking probabilities are at most as high as the minimum of those of the minhop paths, minhop paths are preferred to alternative paths. In particular, if an alternative path of a source–destination shares a bottleneck with one of its minhop paths, this alternative path is automatically pruned. In addition, a source would gradually back off from an alternative path once its observed flow blocking probability starts increasing, thereby adapting gracefully to the change in the network load.

D. Virtual Capacity Based Routing

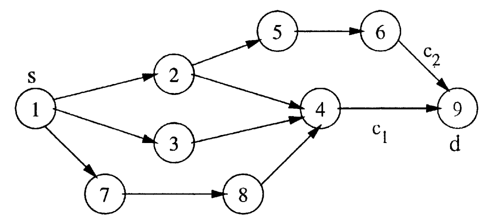
By incorporating this self-refrained alternative routing method into the virtual capacity model, we devise a theoretical adaptive proportional routing scheme, which is referred to as the Virtual Capacity based Routing (vcr) scheme. In this vcr scheme, we use the ebr strategy[4] to proportion flows along the minhop paths, whereas proportions of flows along the alternative paths are computed using the target flow blocking probability ψb^*, as in the self-refrained alternative routing method. The scheme is shown in Fig. 4. Suppose the total load for a source–destination pair is ν. At a given step $n \geq 0$, let $\nu_r^{(n)} = \alpha_r^{(n)} \nu$ be the amount of the load currently routed along a path $r \in R$, and let $b_r^{(n)}$ be its observed blocking probability on the path. Then the virtual capacity of path r is given by $vc_r = E_{vc}^{-1}(\nu_r^{(n)}, b_r^{(n)})$ (line 5). For each minhop path, the mean blocking rate of all the minhop paths $\overline{\beta}^{(n)}$ is used to compute a new target load (lines 6–7). Similarly, for each alternative path, a new target load is determined using the target blocking probability ψb^* (lines 8–9). Given these new target loads for all the paths, the new proportion of flows, $\alpha_r^{(n+1)}$, for each path r is obtained in lines 10–11, resulting in a new load $\nu_r^{(n+1)} = \alpha_r^{(n+1)} \nu$ on path r.

In the following we illustrate through examples how the vcr scheme uses alternative paths in a judicious and self-adaptive manner. First consider the duck topology shown in Fig. 5(a) where there are two minhop and two alternate paths. With the self-refrained alternative routing method, the alternative path $1 \rightarrow 7 \rightarrow 8 \rightarrow 4 \rightarrow 9$, which shares bottleneck link $4 \rightarrow 9$ with

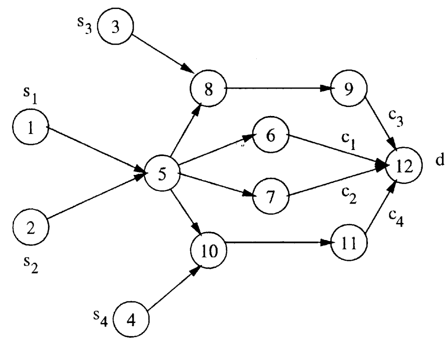
[4] We adopted the ebr strategy as it is found to be more amenable for implementation.

1. PROCEDURE VCR()
2. Set mean block rate of minhop paths, $\bar{\beta}^{(n)} = \frac{\sum_{r \in R^{min}} \alpha_r^{(n)} b_r^{(n)}}{k^{min}}$
3. Set min of minhop path's block probability, $b^* = \min_{r \in R^{min}} b_r^{(n)}$
4. For each path $r \in R$
5. Compute virtual capacity $vc_r^{(n)} = E_{vc}^{-1}(\nu_r^{(n)}, b_r^{(n)})$
6. For each minhop path $r \in R^{min}$
7. Compute target load ν_r^* such that $\bar{\beta}^{(n)} = \nu_r^* E(\nu_r^*, vc_r^{(n)})$
8. For each alternative path $r \in R^{alt}$
9. Compute target load ν_r^* such that $\psi b^* = E(\nu_r^*, vc_r^{(n)})$
10. For each path $r \in R$
11. Compute new proportion $\alpha_r^{(n+1)} = \frac{\nu_r^*}{\sum_{r \in R} \nu_r^*}$
12. END PROCEDURE

Fig. 4. The vcr procedure.



(a)

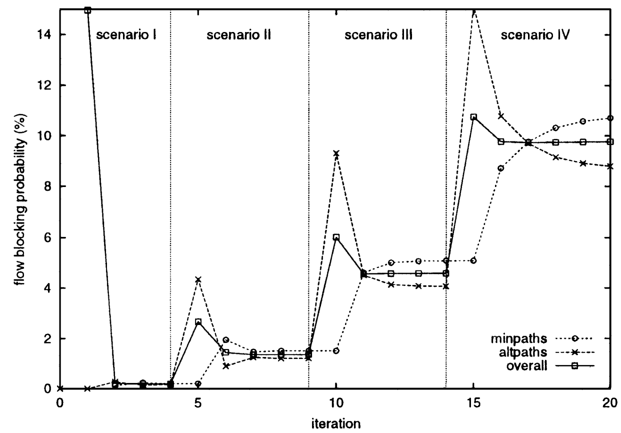


(b)

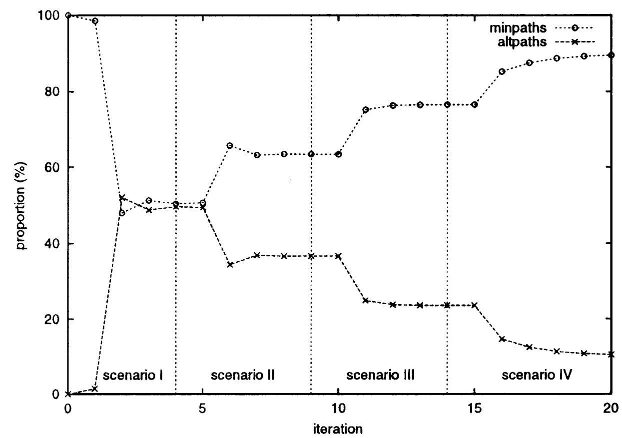
Fig. 5. Topologies used for illustration. (a) Duck. (b) Fish.

minhop paths, is effectively not used for routing since using it would only increase the resource usage without any decrease in the overall blocking probability. In contrast, the alternative path $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 9$ is used to route flows though it shares a link $1 \rightarrow 2$ with a minhop path since the shared link is non-bottleneck. Now we demonstrate how the vcr scheme controls the extent of alternative routing to adapt to the changes in traffic load. Consider the fish topology shown in Fig. 5(b). The nodes 1, 2, 3, and 4 are the source nodes and node 12 is the destination node. Nodes 1 and 2 each have two minhop paths and two alternative paths to the destination node 12. Other two source nodes, 3 and 4, have just one minhop path to the destination node 12. The alternative paths of source nodes 1 and 2 share the bottleneck links $9 \rightarrow 12$ and $11 \rightarrow 12$ with the minhop paths of 3 and 4. Assume that the capacities c_1, c_2, c_3 and c_4 of the bottleneck links are all set to 20. We consider four scenarios where the offered load at source nodes 1 and 2 are fixed at 20 while the offered load at source nodes 3 and 4 are increased from 0 to 5, 10, and 15 in scenarios I–IV respectively, and study how source nodes 1 and 2 adjust their flow proportions on the alternative paths. Fig. 6(a) and (b) show, from the perspective of source node 1, the adaptation process as reflected in the flow blocking probabilities and proportions associated with the minhop paths and the alternative paths. Note that due to the symmetry, source node 2 behaves in exactly the same manner. Hence we will focus only on the behavior of source node 1.

Suppose initially both source nodes 1 and 2 use only their minhop paths. This results in a high blocking probability of 0.1588 on the minhop paths. As both source nodes sense the availability of the alternative paths and start routing flows through them, the blocking probability on the minhop paths drops quickly, resulting in an overall blocking probability of around 0.0019. When source nodes 3 and 4 become active with a load of 5 each, the blocking probability on the two alternative paths shoots up to 0.0435 from 0.0017. The source 1 reacts to this by reducing the proportion of the flows routed to the alternative paths from 0.4964 to 0.3659, pulling the overall blocking probability down to 0.0136. As the load at source nodes 3 and 4 increases further from 5 to 10, then to 15, both source node 1 and source node 2 keep backing off from their alternative paths to yield more capacity share to the minhop paths of source nodes 3 and 4. This example shows that the vcr scheme can adaptively respond to the traffic load changes along the alternative paths by adjusting the proportion of flows routed along these paths. It was argued [30] that selection of maximally disjoint paths yields better blocking performance. The above results show that, using the virtual capacity model and self-refrained alternative routing method, the vcr scheme judiciously proportions traffic among minhop and alternative paths without explicit knowledge about where the shared bottleneck links are.



(a)



(b)

Fig. 6. Illustration of usage of alternative paths in vcr. (a) Convergence process. (b) Adaptation of proportions.

III. Proportional Sticky Routing

In the previous section, we presented an analytical framework for modeling adaptive proportional routing. In particular, based on this framework we described a theoretical adaptive routing scheme—the vcr scheme—and demonstrated its self-adaptivity through several numerical examples. There are two difficulties involved in implementing the virtual capacity model. First, computation of virtual capacity and target load using Erlang's Loss Formula can be quite cumbersome. Second, and perhaps more importantly, the accuracy in using Erlang's Loss Formula to compute virtual capacity and new load relies critically on steady-state observation of flow blocking probability. Hence small statistic variations may lead to erroneous flow proportioning, causing undesirable load fluctuations. In order to circumvent these difficulties, we are interested in a simple yet robust implementation of the vcr scheme. In this section we present such an implementation which we refer to as the proportional sticky routing (psr) scheme.[5]

The psr scheme can be viewed to operate in two stages: 1) proportional flow routing and 2) computation of flow proportions. The proportional flow routing stage proceeds in cycles of variable length. During each cycle incoming flows are routed along paths selected from a set of eligible paths. A path is selected with a frequency determined by a prescribed proportion. A number of cycles form an observation period, at the end of which a new flow proportion for each path is computed based on its observed blocking probability. This is the computation of flow proportion stage. As in the vcr scheme, flow proportions for minhop paths of a source–destination pair are determined using the ebr strategy, whereas flow proportions for alternative paths are determined using a target blocking probability. In the following we will describe these two stages in more detail.

Proportional Flow Routing

Given an arbitrary source–destination pair, let R be the set of candidate paths between the source–destination pair, where $R = R^{\min} \cup R^{alt}$. We associate with each path $r \in R$, a maximum permissible flow blocking number γ_r and a corresponding flow blocking counter f_r. For each minhop path $r \in R^{\min}$, $\gamma_r = \hat{\gamma}$, where $\hat{\gamma}$ is a configurable system parameter. For each alternative path $r' \in R^{\rm alt}$, the value of $\gamma_{r'}$ is dynamically adjusted between 1 and $\hat{\gamma}$, as will be explained later. As shown in Fig. 7(a), at the beginning of each cycle, f_r is set to γ_r. Every time a flow routed along path r is blocked, f_r is decremented. When f_r reaches zero, path r is considered ineligible. At any time only the set of eligible paths, denoted by $R^{\rm elg}$, is used to route flows. A path from current eligible path set $R^{\rm elg}$ is selected using a weighted-round-robin-like path selector [24]. Once $R^{\rm elg}$ becomes empty, the current cycle is ended and a new cycle is started with $R^{\rm elg} = R$ and $f_r = \gamma_r$.

[5]The psr scheme essentially does proportional routing while obtaining proportions through a form of sticky routing.

```
PROCEDURE PSR-ROUTE()
  Select an eligible path r from R^elg
  Increment flow counter, n_r = n_r + 1
  If failed to setup connection along r
    Decrement failure counter, f_r = f_r - 1
    If failures reached limit, f_r == 0
      Remove r from eligible set, R^elg = R^elg - r
      If eligible set is empty, R^elg == ∅
        Reset eligible set, R^elg = R
        For each path r ∈ R
          Reset failure counter, f_r = γ_r
END PROCEDURE
```

(a)

```
PROCEDURE PSR-PROPO-COMPU()
  For each path r ∈ R
    Compute blocking probability, b_r = ηγ_r / n_r
    Assign a proportion, α_r = n_r / Σ_{r̃∈R} n_r̃
  Set target blocking probability, b* = min_{r∈R^min} b_r
  For each alternative path r' ∈ R^alt
    If blocking probability high, b_r' >= b*
      Decrement failure limit, γ_r' = γ_r' - 1
    If blocking probability low, b_r' < ψb*
      Increment failure limit, γ_r' = γ_r' + 1
END PROCEDURE
```

(b)

Fig. 7. The psr procedure. (a) Proportional routing. (b) Computation of proportions.

Computation of Flow Proportions

Flow proportions $\{\alpha_r,\, r \in R\}$ are recomputed at the end of each observation period [see Fig. 7(b)]. An observation period consists of η cycles, where η is a configurable system parameter used to control the robustness and stability of flow statistics measurement. During each observation period, we keep track of the number of flows routed along each path $r \in R$ using a counter n_r. At the beginning of an observation period, n_r is set to 0. Every time path r is used to route a flow, n_r is incremented. Since an observation period consists of η cycles, and in every cycle, each path r has exactly γ_r flows blocked, the observed flow blocking probability on path r is $b_r = \eta\gamma_r/n_r$. For each minhop path $r \in R^{\min}$, its new proportion α_r is recomputed at the end of an observation period and is given by $\alpha_r = n_r/n_{\text{total}}$, where $n_{\text{total}} = \sum_{r\in R} n_r$ is the total number of flows routed during an observation period. Recall that for a minhop path $r \in R^{\min}$, $\gamma_r = \hat{\gamma}$. Hence

$$\alpha_r b_r = \frac{n_r}{n_{\text{total}}}\,\frac{\eta\gamma_r}{n_r} = \frac{n_r}{n_{\text{total}}}\,\frac{\eta\hat{\gamma}}{n_r} = \frac{\eta\hat{\gamma}}{n_{total}}.$$

This shows that the above method of assigning flow proportions for the minhop paths equalizes their flow blocking rates.

As in the vcr scheme, we use the minimum blocking probability among the minhop paths, $b^* = \min_{r\in R^{\min}} b_r$, as the reference to control flow proportions for the alternative paths. This is done implicitly by dynamically adjusting the maximum permissible flow blocking parameter $\gamma_{r'}$ for each alternative path $r' \in R^{alt}$. At the end of an observation period, let $b_{r'} = \eta\gamma_{r'}/n_{r'}$ be the observed flow blocking probability for an alternative path r'. If $b_{r'} > b^*, \gamma_{r'} := \max\{\gamma_{r'}-1,\, 1\}$. If $b_{r'} < \psi b^*$, $\gamma_{r'} := \min\{\gamma_{r'}+1,\, \hat{\gamma}\}$. If $\psi b^* \le b_{r'} \le b^*$, $\gamma_{r'}$ is not changed. By having $\gamma_{r'} \ge 1$, we ensure that some flows are occasionally routed along alternative path r' to probe its "quality," whereas by keeping $\gamma_{r'}$ always below $\hat{\gamma}$, we guarantee that minhop paths are always preferred to alternative paths in routing flows. The new proportion for each alternative path r' is again given by

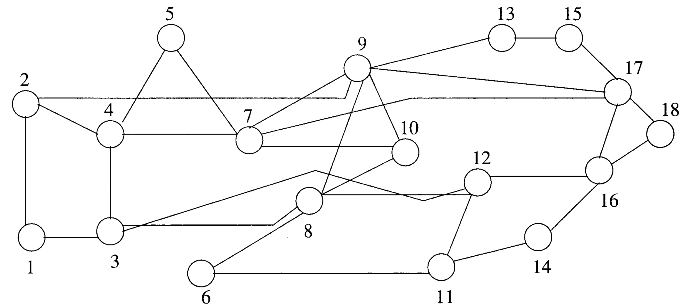


Fig. 8. The isp topology used in our study.

$\alpha_{r'} = n_{r'}/n_{\text{total}}$. Note that since $\gamma_{r'}$ is adjusted for the next observation period, the actual number of flows routed along alternative path r' will be also adjusted accordingly.

Comparison With VCR

The psr scheme preserves the self-adaptivity of the theoretical vcr scheme by controlling the number of flows routed along a path r in each cycle using γ_r and by re-adjusting flow proportions after every observation period. For example, if the load along a path r increases, causing the number of flows blocked to quickly reach γ_r, the source will automatically back off from this path by eliminating it from the eligible path set for the rest of the cycle. If this situation persists, at the end of the observation period, the new flow proportion for path r will be reduced. Likewise, if the load on path r decreases, its new flow proportion will be increased at the end of the observation period. This is particularly true for alternative paths with their dynamically adjusted γ_r. Furthermore, because the length of each cycle is not fixed but determined by how fast each eligible path reaches its maximal permissible blocks, the length of an observation period also varies. This self-adjusting observation period allows the psr scheme to respond to the system load fluctuations in an elastic manner. If the system load changes suddenly, the old flow proportions would result in rapid termination of cycles, which would in turn lead to faster conclusion of the current observation period. New flow proportions will thus be recomputed to adapt to the system load. On the other hand, if the system load is stable, the observation periods will also be stabilized, with increasingly accurate calibration of the flow proportions. As a result, flow proportioning will eventually converge to the equilibrium state.

IV. Performance Evaluation and Analysis

In this section, we evaluate the performance of the proposed localized QoS routing scheme psr and compare it with the global QoS routing scheme widest shortest path (wsp). We first describe the simulation environment and then compare the performance of *psr* and *wsp* in terms of the overall blocking probability, routing stability and overhead.

A. Simulation Environment

Fig. 8 shows the isp[6] topology of an ISP backbone network used in our study (also used in [1], [16]). For simplicity, all the

[6]Simulations were also carried out with other topologies and under different traffic conditions. The results were found to be similar [20] and not included here due to space limitations.

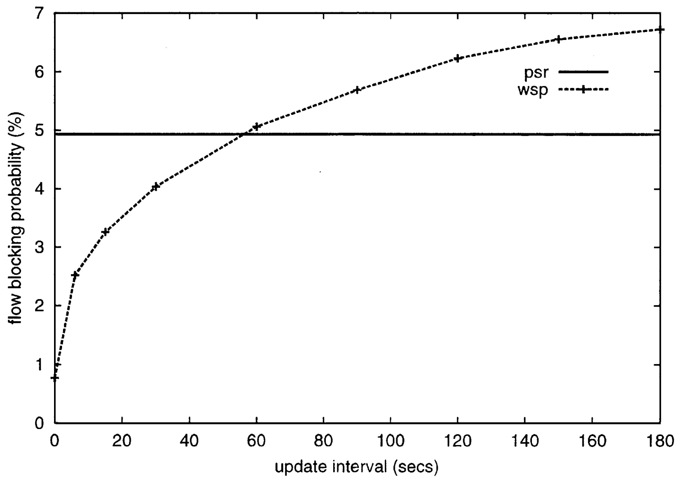


Fig. 9. Impact of update interval on wsp.

links are assumed to be bidirectional and of the same capacity, with C units of bandwidth in each direction. Flows arriving into the network are assumed to require one unit of bandwidth. Hence each link can accommodate at most C flows simultaneously.

The dynamics of flows in the network is modeled as follows (similar to the model used in [28]). A set of nodes in the network is designated as capable of being source/destination nodes of flows. We consider two settings. In the first setting, all nodes are included in this set and in the second setting, only the 9 border nodes, namely 1, 2, 5, 6, 11, 13, 14, 15, and 18 are included. Flows arrive at a source node according to a Poisson process with rate λ. The destination node of a flow is chosen randomly from the designated set of nodes except the source node. The holding time of a flow is exponentially distributed with mean $1/\mu$. Following [28], the offered network load on isp is given by $\rho = \lambda N\overline{h}/\mu LC$, where N is the number of source nodes, L the number of links, and $\overline{h}$ is the mean number of hops per flow, averaged across all source–destination pairs. The parameters used in our simulations are $C = 20$, $N = 18$, $L = 60$, $\overline{h} = 2.36$, $\mu = 60$ s. The average arrival rate at a source node λ is set depending upon the desired load.

The parameters in the simulation are set as follows by default. Any change from these settings is explicitly mentioned wherever necessary. The values for configurable parameters in psr are $\eta = 3$, $\hat{\gamma} = 5$, and $\psi = 0.8$. For each source–destination pair, all the paths between them whose length is at most one hop more than the minimum number of hops are chosen as the candidate paths. The average number of candidate (minhop and minhop+1) paths used in psr are $4.63(1.50 + 3.13)$ and $5.20(1.53 + 3.67)$, respectively, in the first and the second settings of isp. Each run simulates the arrival of 1 000 000 flows, and the results corresponding to the latter half of the simulation are reported here.

B. Blocking Probability

The performance of wsp and psr is compared by measuring the blocking probability under various settings. We first present the impact of update interval on the performance of wsp and show how the blocking probability increases rapidly as update interval is increased. We then demonstrate the adaptivity of psr by varying the overall load. Finally we compare the performance of these two schemes under nonuniform load conditions and show that psr is better at alleviating the effect of "hot spots."

Varying Update Interval: Fig. 9 compares the performance of wsp and psr with the offered load set to 0.60. The performance is measured in terms of the overall flow blocking probability, which is defined as the ratio of the total number of blocks to the total number of flow arrivals. The overall blocking probability is plotted as a function of the update interval used in wsp for periodic updates.[7] From the figure, we see that, as the update interval of wsp increases, the blocking probability of wsp rapidly approaches that of psr and gets worse for larger update intervals.

Varying Offered Load: We now illustrate the adaptivity of *psr* by varying the offered load. We initially offer a load of 0.60 as was done in the earlier simulation and then this overall load is decreased to 0.50 and again increased to 0.65. We plot the blocking probability under psr and wsp as a function of time in Fig. 10(a). The performance of wsp is shown for two update intervals: 30 and 60 s. Starting with arbitrary initial proportions, psr quickly converges and performs as well as wsp(60). When the load is decreased, psr adapts to the change and maintains

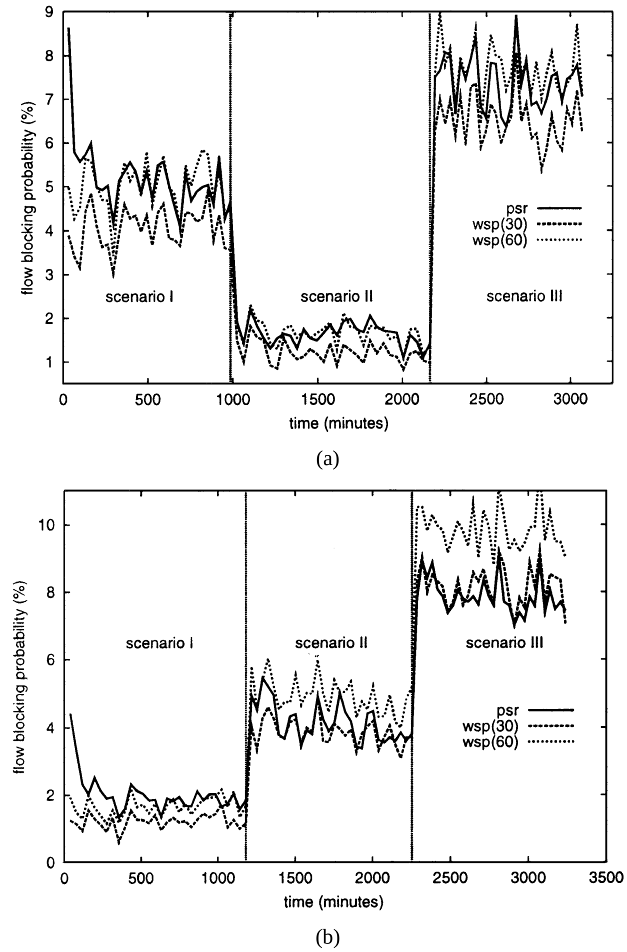


Fig. 10. Performance under varying load. (a) Uniform. (b) Nonuniform.

[7]Note that blocking performance of wsp with threshold triggered updates with hold-down timer T would be no better than periodic updates with update interval T. The difference is in the amount of update message overhead.

its relative performance. Finally, when the load is increased to 0.65, once again it reacts promptly and performs slightly better than wsp(60).

Varying Nonuniform Traffic: It is likely that a source node receives a larger number of flows to a few specific destinations [4], i.e., a few destinations are "hot." Ideally, a source would like to have more up-to-date view of the QoS state of the links along the paths to these "hot" destinations. In the case of wsp, this requires more frequent QoS state updates, resulting in increased overhead. But in the case of psr, because of its adaptivity and statistics collection mechanism, a source does have more accurate information about the frequently used routes and thus alleviates the effect of "hot spots." We illustrate this by introducing increased levels of traffic between certain pairs of network nodes ("hot pairs"), as was done in [1]. Apart from the normal load that is distributed between all source–destination pairs, an additional load (hot load) is distributed among all the hot pair nodes. The hot pairs chosen are (2, 16), (3, 17), and (9, 11).

We consider three scenarios. In scenario I, a load of 0.50 is offered uniformly among all the nodes as was done in earlier simulations. In scenario II, an additional load of 0.05 is offered between hot pairs only and in scenario III this additional load is further increased to 0.10. Fig. 10(b) shows the blocking performance of the two schemes under different scenarios as a function of time. Under scenario I, starting with arbitrary initial proportions, psr quickly converges to a stable state where its blocking probability is similar to that of wsp(60). But, in scenario II, with additional load between hot pairs, psr approaches the performance of wsp(30) and even better in scenario III where the load between hot pairs is higher. These results illustrate the degradation in performance of wsp and improvement in relative performance of psr under nonuniform load conditions.

Various Load Conditions: We have further investigated the impact of traffic pattern on the relative performance of these schemes by offering various loads. First, we consider the setting where load is offered uniformly between all the nodes. Fig. 11(a) shows the blocking performance as a function of the offered network load. As before, the performance is measured in terms of the overall flow blocking probability. The network load is varied from 0.50 to 0.70. The performance of wsp is plotted for three update intervals of 30, 60 and 90. It is clear that psr performs as well as wsp(60) at low loads and better at high loads. Next, we consider the setting where load is offered only between the border nodes. This is a reasonable setting since these edge nodes are likely to be ingress and egress nodes for flows passing through this domain. We ran the simulations varying the load on border nodes from 0.35 to 0.40. Fig. 11(b) shows the results of these simulations. It can be seen that, across all loads, psr performs better than wsp with a 30-s update interval. We then fixed the load on border nodes at 0.35 and varied the additional load offered on hot pairs. Fig. 11(c) shows the blocking performance of the schemes as a function of the additional load. When there is no additional load on hot pairs, performance of psr is similar to wsp(30). As the additional load on hot pairs increases, psr does progressively better in comparison to wsp and at hot load of 0.10 it performs as well as wsp with an update interval of 15 s and even better at higher hot loads. This not only shows the limitation of global routing schemes such as wsp but also illustrates the self-adaptivity of localized proportional routing schemes such as psr.

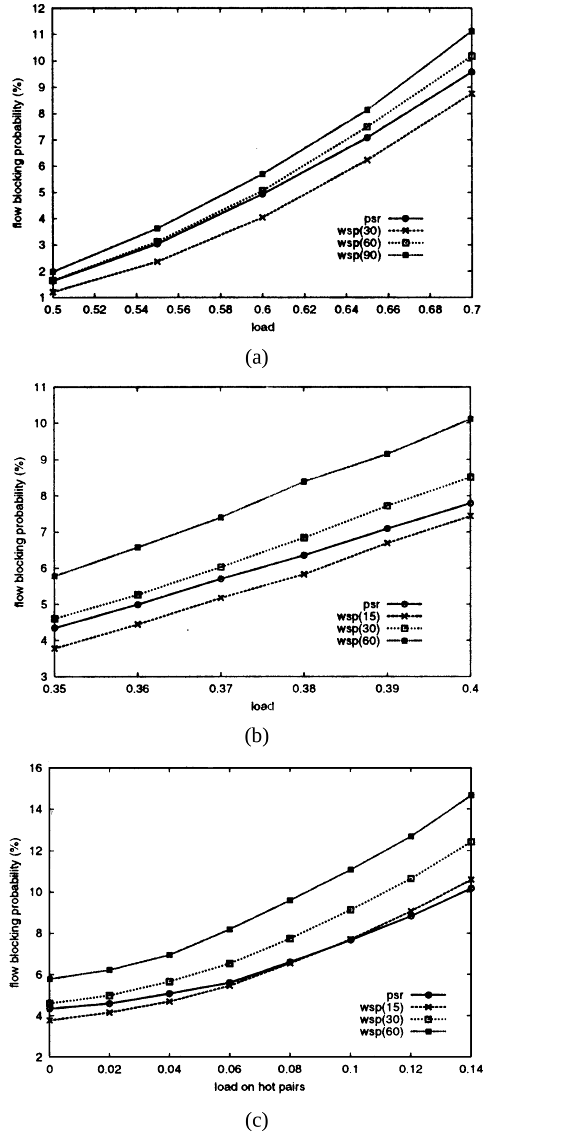


Fig. 11. Performance under various loads. (a) Uniform traffic. (b) Fewer sources. (c) Hot pairs.

C. Heterogeneous Traffic

The discussion so far is focused on the case where the traffic is homogeneous, i.e., all flows request for one unit of bandwidth and their holding times are derived from the same exponential distribution with a fixed mean value. Here we study the applicability of psr in routing heterogeneous traffic where flows could request for varying bandwidths with their holding times derived from different distributions. We demonstrate that psr is insensitive to the duration of individual flows and hence we do not need to differentiate flows based on their holding times. We also show that when the link capacities are considerably larger than the average bandwidth request of flows, it may not be necessary to treat them differently and hence psr can be used as is to route heterogeneous traffic.

Consider the case of traffic with k types of flows, each flow of type i having a mean holding time $1/\mu_i$ and requesting bandwidth B_i. Let ρ_i be the offered load on the network due to flows of type i, where the total offered load, $\rho = \sum_{i=1}^{k} \rho_i$. The fraction of total traffic that is of type i, $\phi_i = \rho_i/\rho$. The arrival rate of type i flows at a source node, λ_i is given by $\lambda_i = \rho_i \mu_i LC/N\overline{h}B_i$, which is an extension of the formula presented in Section IV-A. To account for the heterogeneity of traffic, bandwidth blocking ratio [16] is used as the performance metric for comparing different routing schemes. The bandwidth blocking ratio is defined as the ratio of the bandwidth usage corresponding to blocked flows and the total bandwidth usage of all the offered traffic. Suppose b_i is the observed blocking probability for flows of type i, then the bandwidth blocking ratio is given by

$$\frac{\sum_{i=1}^{k} \frac{b_i \lambda_i B_i}{\mu_i}}{\sum_{i=1}^{k} \frac{\lambda_i B_i}{\mu_i}}.$$

In the following, we compare the performance of psr and wsp, measured in terms of bandwidth blocking ratio, under different traffic conditions, varying the fractions ϕ_i to control the traffic mix.

Mixed Holding Times: We now examine the case of traffic with two types of flows that request for the same amount of bandwidth, i.e., $B_1 = B_2 = 1$, but with different holding times. We consider three scenarios. In the first scenario, both types of flows have their holding times derived from exponential distribution but their means are different: 60 and 120 s. In the second scenario, both types have the same mean holding time of 60 s but their distributions are different: exponential and pareto. In the third scenario, holding times of both types of flows follow pareto distribution but their means are different: 60 and 120 s. In all these scenarios, a load of 0.40 is offered between the border nodes in isp. Fig. 12 shows the performance of psr and wsp under different scenarios.

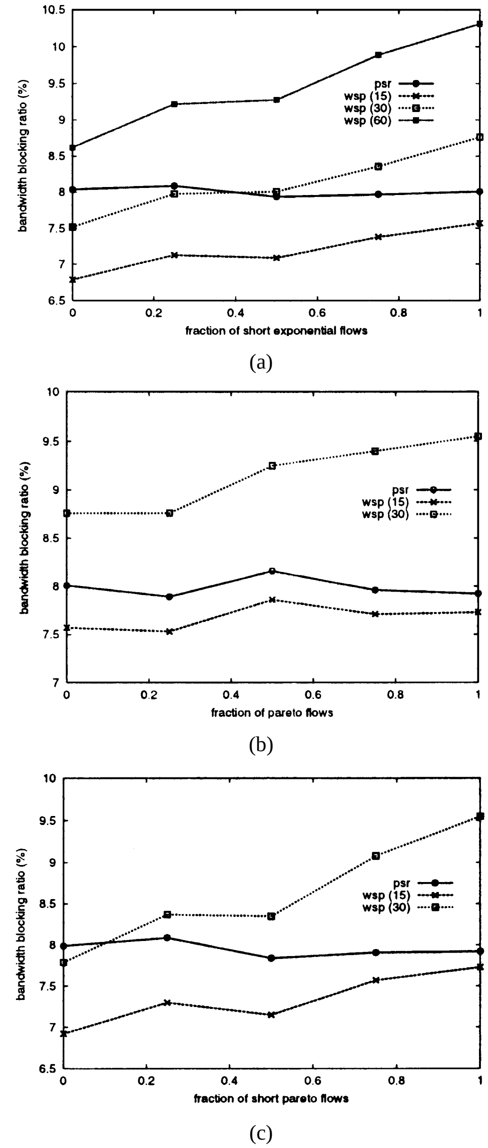


Fig. 12. Traffic with mixed holding times. (a) Long and short exponential. (b) Exponential and pareto. (c) Long and short pareto.

Consider the first scenario where type 1 flows are short ($1/\mu_1 = 60$ s) and type 2 flows are long ($1/\mu_1 = 120$ s), but both are exponentially distributed. Fig. 12(a) shows the bandwidth blocking ratio plotted as a function of the fraction ϕ_1 corresponding to short flows. It is quite evident that the performance of wsp degrades as the proportion of short flows increases while that of psr stays almost constant. The behavior of wsp is as expected since the shorter flows cause more fluctuation in the network QoS state and the information at a source node becomes more inaccurate as the QoS state update interval gets larger relative to flow dynamics. On the contrary, psr is insensitive to the duration of flows.

In the second scenario, a fraction of flows have their holding times derived from a pareto distribution while the rest have their holding times derived from an exponential distribution. The mean holding time of both the types is the same, 60 s. The pareto distribution is long tailed with its tail controlled by a shape parameter. We have experimented with different shape values in the range 2.1 to 2.5 and found that results are similar. The results reported here correspond to a shape value of 2.2. In Fig. 12(b), bandwidth blocking ratio is plotted as a function of the fraction of pareto type flows. As the fraction of pareto flows increases, the blocking under wsp(30) increases while it stays almost same under wsp(15). The number of short (much less than mean holding time) flows are more under the pareto distribution than the exponential distribution because of the long tail of pareto. Consequently, update interval has to be small to capture the fluctuations due to such short flows. That is why the performance of wsp(30) degrades while wsp(15) is not affected. The relative performance of these schemes in the third scenario is similar to the first scenario with short and long flows. An important thing to note is that in all the scenarios the performance of psr is insensitive to the holding times of flows.

The behavior of psr is not surprising since the Erlang formula is known to be applicable even when the flow holding times are not exponentially distributed and blocking probability depends only on the load, i.e., the ratio of arrival rate and service rate. For the above case of two types of flows, the aggregate arrival

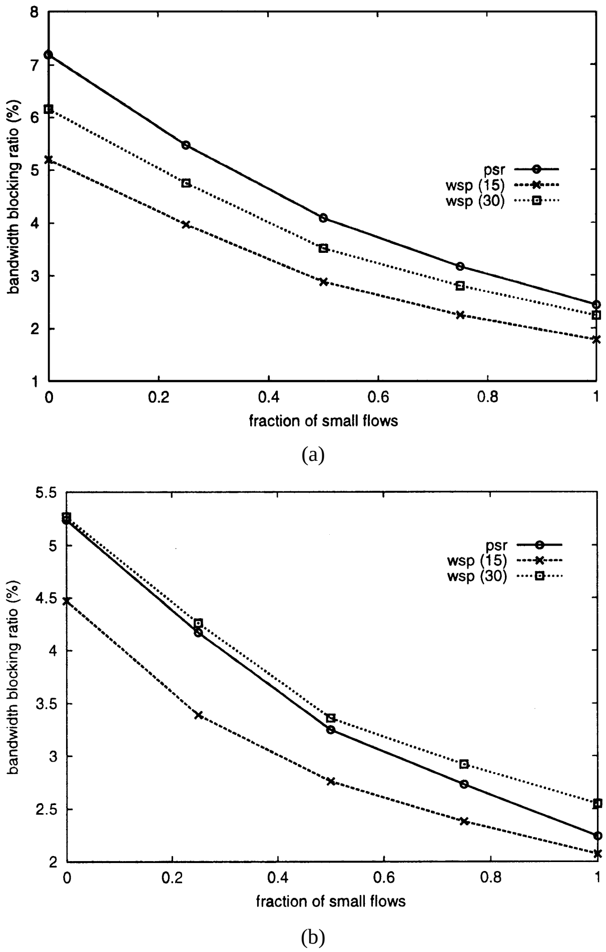


Fig. 13. Variable bandwidth traffic. (a) $C = 20$. (b) $C = 40$.

rate λ is given by $\lambda = \lambda_1 + \lambda_2$ and the mean holding time $1/\mu$ is given by

$$\frac{1}{\mu} = \frac{1}{\mu_1}\,\frac{\lambda_1}{\lambda_1 + \lambda_2} + \frac{1}{\mu_2}\,\frac{\lambda_2}{\lambda_1 + \lambda_2}.$$

This heterogeneous traffic can then be treated as equivalent to homogeneous traffic with arrival rate λ, mean holding time $1/\mu$, and the corresponding load $\lambda/\mu = \lambda_1/\mu_1 + \lambda_2/\mu_2$. So for a given load, the blocking probability would be the same irrespective of the mean holding times of individual flows. That is why the performance of the theoretical scheme, vcr depends only on the overall offered load and not on the types of traffic. The practical scheme, psr also behaves similarly and hence psr can be employed as is to route flows with mixed holding times.

Varying Bandwidth Requests: Now, consider the case of traffic with 2 types of flows, each requesting for different amount of bandwidth but having the same mean holding time. The bandwidth requests of flows are derived uniformly from a range: 0.5 to 1.5 for small flows and 1.5 to 2.5 for large flows, i.e., the mean bandwidth of small flows is 1 while it is 2 for large flows. The holding times of all the flows are drawn from an exponential distribution with mean 60 s. The performance is measured varying the mix of small and large flows. Fig. 13(a) shows the bandwidth blocking ratio as a function of the fraction of small flows. First thing to note is that psr performs poorly when the majority of flows are large. However, as the number of small flows increases, it approaches the performance of wsp(30). The reason is that routing under psr is independent of the amount of bandwidth requested while wsp is conscious of the bandwidth requested. However, when the link capacity is much larger than a flow's bandwidth request, psr performs fine even though it is unconscious of the requested amount. To illustrate this, we increased the capacity of all links to 40 and measured the performance of both the schemes under similar load conditions as in the previous case. Fig. 13(b) shows that psr performs as well as wsp(30) when all the flows are large and approaches wsp(15) as the number of small flows increases. In the following, we argue further that when bandwidth requests are significantly smaller than the link capacity, it is not necessary for psr to differentiate between different bandwidth requests.

In [26], it was shown that when the capacity of a link is large, the blocking probability of a flow of type i can be approximated as follows. Suppose that type i flow requests for d_i units of bandwidth and the load of type i flows on link l is ν_l^i. The blocking probability for type i flows on link l is given by

$$b_l^i = \frac{d_i}{\delta}\, E\left(\frac{\sum \nu_l^i d_i}{\delta}, \frac{c_l}{\delta},\right)$$

where δ is an "equivalent rate" given by

$$\delta = \frac{\sum \nu_l^i d_i^2}{\sum \nu_l^i d_i}.$$

In other words, the ratio of blocking probabilities of flow types i and j would be same as the ratio of their bandwidth requests, i.e., $b_i/b_j \approx d_i/d_j$. This implies that $\lambda_1 b_1/\lambda_2 b_2 = \phi_1/\phi_2$, i.e., the blocking rate of flows of a type is proportional to their fraction in the total offered load. Consequently, performance of a equalization based proportional routing scheme would be same with or without categorizing the flows into different classes. However, psr has to be extended to route flows with relatively large bandwidth requests, since it is possible that a path that is good for one bandwidth request may not be even feasible for another bandwidth request. In such a case, since the amount of bandwidth requested by a flow is known at the time of path selection, it makes sense to utilize this knowledge in categorizing them into bandwidth classes and routing them accordingly. Considering that in practice link capacities are much larger than an individual flow's bandwidth request, psr can be used as is to route heterogeneous traffic in most cases.

D. Sensitivity of PSR

We now study the sensitivity of psr to the settings of its configurable parameters, η and $\hat{\gamma}$. These parameters control the observation period between successive computations of proportions. While η specifies the number of cycles in an observation period, $\hat{\gamma}$ gives the number of blocks permitted per path in a cycle and thus indirectly controls the length of a cycle. We have experimented with several settings of (η, $\hat{\gamma}$) and here we present the results of three different settings: (1, 1), (3, 5), and (5, 10) in Fig. 14. Two separate graphs are shown for readability. The traffic patterns and loads are varied to see the adaptivity of psr under different settings. In scenario I, a load of 0.35 is offered between border nodes and in scenario II, an additional load of

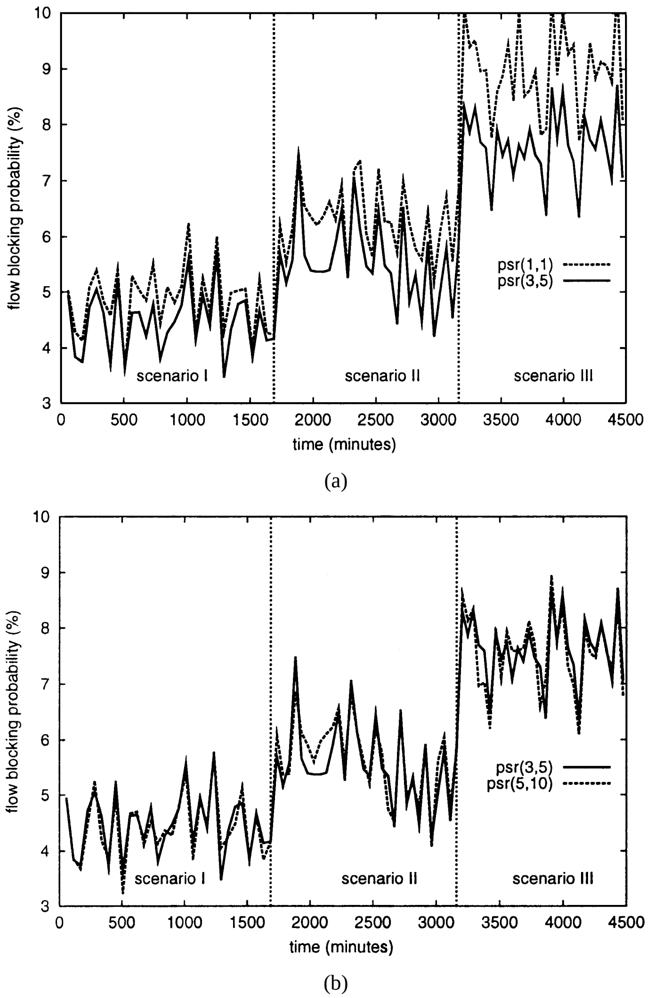


Fig. 14. Performance of psr under different (η, $\hat{\gamma}$) settings: (a) (3, 5) versus (1, 1) and (b) (3, 5) versus (5, 10).

0.05 is offered between hot pairs only and this hot load is increased to 0.10 in scenario III. Under all settings, psr adapts quickly to traffic scenario changes. But psr(3, 5) blocks lesser flows than psr(1, 1) while no discernible difference between psr(3, 5) and psr(5, 10). The performance difference between psr(1, 1) and psr(3, 5) is more evident in scenario III where the overall offered load is high. In general, fewer the blocks permitted in a cycle, lesser the effect of proportional routing. Relatively longer cycles are needed to get a good estimate of right proportions. Also, from the perspective of stability it is better to change proportions gradually to reduce oscillations. From these results, we observe that 3 cycles and 5 blocks per path per cycle seem to work fine and beyond that psr is relatively insensitive to its parameter settings.

E. Routing Stability

An essential feature of a good routing scheme is its ability to avoid routing oscillations and thus ensure stability. It was shown [29] that out-of-date information due to larger update intervals can cause route flapping in schemes such as wsp. When the utilization on a link is low, an update causes all the source nodes to prefer routes along this path, resulting in a rapid increase in its utilization. Similarly when the utilization is high, an update causes all the sources to shun this link and consequently its utilization decreases as the existing flows depart. This synchronization problem is inherent in any global information exchange based QoS routing schemes such as wsp. On the other hand, the psr scheme does not exhibit such route flapping behavior. There are two fundamental reasons for the stability of psr. First, in psr each source performs routing based on its own local view of the network state. Routing based on such a “customized view” avoids the undesirable synchronized mass reaction that is inherent in QoS routing scheme based on a global view. Second, psr does proportional routing with a proportion assigned to a path reflecting its quality. A relatively better path is favored by sending larger proportion of traffic to it. It does not pick just one “best” path. The psr can also cause higher fluctuation occasionally at the end of a cycle due to making some paths ineligible and routing all the load along one or a few eligible paths. However, as proportions stabilize, duration of such fluctuations tend be smaller. Considering all this we claim that a localized proportional routing scheme such as psr is intrinsically more stable than a global best-path routing scheme such as wsp.

F. Routing Overhead

We now take a close look at the amount of overhead involved in these two routing schemes. This overhead can be categorized into path selection overhead and information collection overhead. We discuss these two separately in the following.

The wsp scheme selects a path by first pruning the links with insufficient available bandwidth and then performing a variant of Dijkstra’s algorithm on the resulting graph to find the shortest path with maximum bottleneck bandwidth. This takes at least $O(E \log N)$ time where N is the number of nodes and E is the total number of links in the network. Assuming precomputation of a set of paths R to each destination to avoid searching the whole graph for path selection, it still need to traverse all the links of these precomputed paths. This amounts to an overhead of $O(L)$, where L is the total number of links in the set R. On the other hand, the path selection in psr is simply an invocation of weighted—round—robin—like path selector [24] whose worst case complexity is $O(|R|)$ which is much less than $O(L)$ for wsp.

Now consider the information collection overhead. In wsp, each source acquires a network-wide view on the status of links through link state updates. Every router is responsible for maintaining QoS state and generating updates about all the links adjacent to it. These updates are sent either periodically or after a significant change in the resource availability since the last update. They are propagated to all the routers in the network through flooding. As in OSPF [17], each router is responsible for maintaining a consistent QoS state database. This incurs both communication and processing overhead. In contrast, the routers employing psr scheme do not exchange any such updates and thus completely do away with this overhead. Only source routers need to keep track of route level statistics and recompute proportions after every observation period. Statistics collection in psr involves only increment and decrement operations costing only constant time per flow. The proportion computation procedure in psr itself is extremely simple and costs no more than $O(|R|)$.

V. Related Work

The problem of QoS routing has been addressed in several contexts, a survey of which can be found in [12]. The work more relevant to ours is the distributed routing scheme proposed in [13] where a set of multiple paths are probed in parallel, using tickets, for a satisfactory path. However, this approach requires the distribution and processing of these tickets by intermediate nodes. Minimum interference routing [9] is a scheme proposed recently that selects a path that interferes least with the routing of future flows. While this scheme provides good routing performance, it has significant computational overhead. The proportional routing approach presented in this paper achieves the similar effect by gradually adapting the flow proportions assigned to paths based on their blocking probabilities which is an indirect measure of interference of paths.

The proportional routing schemes have been studied (see [3] and [15] and references therein) in the context of telephone networks. The dynamic alternative routing (dar) is a well known routing scheme [7] where a source always tries the direct one-link path to the destination first and in case of a crankback chooses a two-link path using sticky routing. This scheme essentially sticks to a path as long as it can accommodate offered traffic. An application of automata to the routing problem is given in [18]. The incoming flows are offered to a path r according to a probability distribution p_r, which is updated using feedback information regarding flow admission or rejection. They reward a path on which a flow is successful and punish a path on which a flow fails. These schemes are mainly designed for fully connected networks and not well-suited for networks like Internet that may have more than one minhop path and many alternative paths between each source–destination pair. A comparison of these schemes with psr scheme can be found in [24].

VI. Conclusion

This paper focused on localized QoS routing schemes where the edge routers make routing decisions using only "local" information. As a first step toward designing a simple localized scheme, we developed vcr, a theoretical scheme based on the notion of virtual capacity of a route. We then proposed psr, an easily realizable approximation of vcr, and analyzed its performance. We demonstrated through extensive simulations that the psr scheme is indeed simple, stable, and adaptive. We have also shown that the proposed scheme is insensitive to the durations of flows and also that when the link capacities are significantly larger than bandwidth requests of flows, the psr scheme can be employed as is to route heterogeneous flows. We have compared the performance of psr with wsp and shown that psr performs as well as wsp even at smaller update intervals. In particular, we found that psr performs better than wsp when higher load is offered from fewer sources and when the flows are of shorter duration and smaller bandwidth. We conclude that the psr scheme, with low overhead and comparable performance, is a viable alternative to global QoS routing schemes such as wsp.

The localized approach to proportional routing is simple and has several important advantages. However it has a limitation that routing is done based solely on the information collected locally. A network node under localized QoS routing approach can judge the quality of paths only by routing some traffic along them. It would have no knowledge about the state of the rest of the network. While the proportions for paths are adjusted to reflect the changing qualities of paths, the candidate path set itself remains static. To ensure that the localized scheme adapts to varying network conditions, many feasible paths have to be made candidates. It is not possible to preselect a few good candidate paths statically. Hence it is desirable to supplement localized proportional routing with a mechanism that dynamically selects a few good candidate paths. We proposed such a hybrid approach in [22] where a few widest disjoint paths are selected as candidates based on infrequently globally exchanged link state metrics and flows are proportioned among these candidate paths based on locally collected path state metrics. We have also extended our proportional routing approach to provide hierarchical routing across multiple areas in a large network. More details can be found in [23].

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