State-dependent Optimal Routing in MPLS-based IP Networks with Heterogeneous Flow Holding Times

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Abstract: **This study investigates routing in a MPLS-based (Multi-Protocol Label Switching)IP network with heterogeneous holding time traffic (for example, an IP call versus an IP conference). Our basic idea is to exploit the large differences existing in the holding time of different types of traffic to make more efficient resource allocation decisions in the admission and routing processes. In particular, we investigate the concept of vacating, in which requests with short holding times vacate the bandwidth to requests with long holding times. Based on an analytical framework we developed, we analyze the vacating idea and propose several state-dependent routing schemes, namely preventive-vacating routing (PVV), preemptive-vacating routing (PEV) and restricted-access routing (RAR). Both the analytical and simulation results indicate that within an effective range we found in traffic mix, our vacating schemes outperform the traditional LLR+TR (least loaded routing + Trunk Reservation) and Diff-SDR (differentiated dynamic shortest-distance routing scheme) [7]. Moreover, we deduce an approximated expression to compute the cost of accepting a long or short request, which leads to an approximated least cost routing (A-LCR) scheme. Through simulation study, A-LCR presents not only its good performing in network throughput, but also its particular flow control mechanism.**

Keywords: state-dependent routing, heterogeneous holding-time, MPLS-based IP network, Cost, MDP.

I. INTRODUCTION

The traditional Internet, which in the past has supported only a best effort service, has transformed very quickly into commercial broadband multi-service IP networks demanding support for quality of service (QoS). A variety of challenges have been experienced by such multi-service IP networks in dealing with much more complicated routing. One of the main issues concerning routing is how to dispose of traffic heterogeneity.

Traffic heterogeneity includes both the differences in bandwidth requirements among flows, which have been studied broadly and heuristically [1,2,15,16,17,18,19,20,21, 22,23,24], as well as the differences in holding time among flows, which have not yet attracted enough necessary attention. Our major goal in this paper is to study the following routing issue: how we can take the large heterogeneity of holding time among traffic flows (for example, an IP call versus an IP conference) into consideration when making routing decisions in a MPLS-based (Multi-Protocol Label Switching) IP network.

Traffic with heterogeneous holding times belongs to the multi-service traffic. There are, in general, two categories of methods used to study the routing issues in multi-service networks. The first is the Markov Decision Process-based (MDP) approach. The MDP approach formulates the routing problem as a Markov decision process and obtains the “cost” for carrying a connection by the network. According to the Markov decision theory [14], an optimal routing policy, which minimizes the expected “cost”, can be found with a finite number of policy iterations. Literature about the MDP approach is rich both in telephone networks [9,21,25] and in multi-service networks [1,2,17,18,19,20,21,22,23,24].

The second can be called the “packing” approach. This approach is based on the observation that in order to maximize the utilization of available resources, a routing policy in a multi-rate environment should implement packing of narrow band traffic (having relatively small bandwidth requirement) on some routes so as to leave room on other routes for wideband traffic (having relatively large bandwidth requirement). Examples of schemes [4,5] using the packing technique are Most-Loaded Routing (MLR), Multi-Rate Least-Loaded Routing with Packing (MLLRP), and Load Profiling Routing. These packing schemes can be considered as the improvements on the well-known LLR+TR (Least Loaded Routing + Trunk Reservation) routing, which is very efficient for single-rate telephone networks [3], but not necessarily the best scheme for multi-rate networks [5].

Most of the work on multi-service networks focuses on the multi-rate traffic. Only a few [6, 7] pay attention to the non-homogenous holding times of traffic. In [6], the authors introduce a new hybrid approach that performs dynamic routing only to long holding time flows, while forwarding short holding time flows on static pre-provisioned routes.

In [7], a differentiated dynamic shortest-distance routing scheme (Diff-SDR) is proposed. The distance is defined as the reciprocal of the residual bandwidth of the link. Differentiated link metrics are used to compute the shortest distance. For short requests, the link metric is the most up-to-date. While for long requests, the link metric is averaged over a given time scale.

Our basic idea is the concept of vacating (and associated vacating routing schemes), in which requests with short holding times vacate the bandwidth on direct links in favor of requests with long holding times under some traffic conditions. This belongs to the packing approach generally. Besides, based on the MDP work on multi-service routing [2], we deduce an approximated expression to compute the cost of accepting a long or short request. This leads to an approximated least cost routing (A-LCR) scheme directly. For all the routing schemes we proposed, computer simulations are run to validate them and compare them thoroughly with LLR+TR, Diff-SDR and re-routing schemes [11], which have never been done, to our best knowledge, in heterogeneous holding time traffic environment.

The remainder of this paper is organized as follows. In Section II, we describe the associated system model in details. Then we develop an analytical framework to analyze our vacating idea and present the proposed routing schemes in Section III. In Section IV, A-LCR scheme is shown. The simulation results are presented in Section V. Finally, main conclusions are drawn in Section VI.

II. SYSTEM MODEL

We consider a well-connected and well-engineered packet-switched network. By network, we mean here a collection of nodes and links placed under a common administrative domain, often referred to as an autonomous system (AS). By well-connected, we mean that many origin-destination pairs are directly connected and many two-link paths exist for each origin-destination pair. We thus only consider either a direct route or a two-hop route in the network. By well-engineered, we essentially mean that the links are placed and sized so that the bulk of the traffic can be carried over a shortest path, most often of one link. Both of these assumptions are readily satisfied in many backbone IP networks.

We consider only the connection traffic sources, which generate a long series of packets over some time interval. We assume that the arrivals of connection traffic requests are Poisson, and the holding times of connection traffic requests are independent and exponentially distributed. Connection traffic is characterized by several parameters:

- Bandwidth required.
- Origin in network: usually fixed.
- Destination in network: usually fixed.
- Holding time.

The bandwidth that a connection requires can be defined in terms of an "equivalent bandwidth" in the sense of Kelly [12]. That is, if a connection is provided its equivalent bandwidth, then its quality of service objectives are met. We also assume that the traffic generated by each traffic source is small compared to the capacity of the links that it may use. This is easy to justify based on the fact that a network needs by definition to share its resources among a large number of concurrent users.

There can be lots of variations among mean holding times of different requests. For example, holding times may varies from days (e.g., VPN), to hours (videoconference), to minutes (Voice over IP call), to seconds (HTTP). Please note that in this study, we talk about the case in which different types of connections have widely differing holding times, and we assume that this is known by the system. In practice, the holding time may be explicitly negotiated as part of the admission process or the service agreement (being a parameter announced by the traffic source, e.g., a 2-hours videoconference). Or, the holding time may be known implicitly through attributes of the connection such as the protocol and port used. (e.g., a TCP port). Furthermore, we care about not the exact value of holding time of each connection, but the mean value of a category of connections, which can be obtained basing on the long-term statistical measurements.

For simplicity, we divide the traffic in our model into two categories: the one with a longer exponentially-distributed holding time is called long request traffic, with mean holding time h_L. The other with a shorter exponentially-distributed holding time is called short request traffic, with mean holding time h_S. In addition, $h_L >> h_S$. Thus, an offered load ρ_L Erlang by long requests is given by $\rho_L = \lambda_L \times h_L$, where λ_L is the average Poisson arrival rate of long requests. An offered load ρ_S Erlang by short requests is given by $\rho_S = \lambda_S \times h_S$, where λ_S is the average Poisson arrival rate of short requests. We also define the holding time ratio as $x = h_L / h_S$, and the traffic mix as $y = \rho_L / (\rho_L + \rho_S)$.

Our model supports the MPLS mechanism [13], and we suppose the route selection process is state-dependent. That is, the outcome of the process can depend on the current offered traffic and loading conditions on the various links of the network. For connection traffic, routing decisions apply on the basis of the connection level. If a connection request is accepted and a route is assigned for it, then the bandwidth on each link of the route is simultaneously held for the duration of the connection. When the connection request is finished, the bandwidth it held on each link should be released, so as to be re-used by other requests. If a connection request is blocked due to lack of bandwidth, then it is lost.

The primary performance measure is the network throughput, i.e. the fraction of the total offered load that is routed/accepted, which is computed according to: $\frac{No.\ of\ carried\ long\ requests \times x + No.\ of\ carried\ short\ requests}{No.\ of\ offered\ long\ requests \times x + No.\ of\ offered\ short\ requests}$.

Besides, the fairness of routing scheme is good or not is decided by whether the individual blocking rates of long and short requests are equal or not. Additionally, we use the network throughput of LLR+TR scheme as a baseline for performance comparison purpose. Thus, we further define the outperformance metric as:

$$Outperformance\ of\ a\ proposed\ routing\ scheme\ compared\ to\ LLR+TR(\%) = (Network\ Throughput\ by\ this\ scheme) - (Network\ Throughput\ by\ LLR+TR).$$

III. VACATING ROUTING

A simple routing scenario (Figure 1) is used to present our vacating idea. In Figure 1, we suppose that only one bandwidth unit is left on $route_{O,D}$ and $route_{O,T,D}$. In addition, there are two Poisson-type traffic from node O to node D: long request flows with mean arrival rate λ_L and mean holding time h_L, and short request flows with mean arrival rate λ_S and mean holding time h_S. Now, a new *O-to-D* request (either a long or a short one) arrives, with required equivalent bandwidth b (one unit) and mean holding time h (h_S or h_L), then how to select an appropriate route for it?

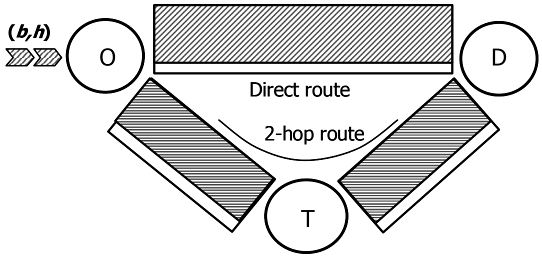

Figure 1. A simple routing scenario. (O,T,D are three nodes connected by three links(from O to D). b is the equivalent bandwidth, h is the holding time, the shadowed area is the occupied bandwidth on the link.)

We can envision the following two routing options to address the above question:

1. allocate the request to the direct route, which is the shortest path (this is what LLR will do).
2. use the two-hop route to serve the short request, and vacate bandwidth in the direct route for upcoming long requests. (our vacating idea)

We claim that option 2 should provide a superior performance to option 1 under certain conditions.

A. Analytical Framework

To draw an analytical framework enabling the analysis of the ideas expressed above, we use a concept called cost rate (c_r) to deal with the resource utilization cost of accepting a long request or short request flow. That is to say, the cost of accepting a request is approximately proportional to the holding time of this request [1]. In detail, the cost of accepting a long request flow is $c_r \times h_L$, and the cost of accepting a short request flow is then $c_r \times h_S$. Obviously, since $h_L >> h_S$, the cost induced by a long request is much bigger than the cost by a short request. In Figure 1, suppose that the cost rate on $route_{O,D}$ is c_{r1}, and it is c_{r2} on the two-hop route $route_{O,T,D}$. c_{r2} is the sum of cost rates on $link_{O,T}$ and $link_{T,D}$. Hence, $(c_{r2}-c_{r1})>0$ is generally true in most cases, especially under a heavy traffic load. As Poisson traffic flows, we have:

- Pr(a request arriving during $h) = (1-e^{-\lambda h})$, where $\lambda = \lambda_L + \lambda_S$
- Pr(a short request arriving first during $h) = (1-e^{-\lambda h}) \times p$;
- Pr(a long request arriving first during $h) = (1-e^{-\lambda h}) \times (1-p)$;
- $p = \frac{\lambda_S}{\lambda_S+\lambda_L} = \frac{\lambda_S}{\lambda}$ and $(1-p) = \frac{\lambda_L}{\lambda_S+\lambda_L} = \frac{\lambda_L}{\lambda}$.

Then the cost induced by option 1 is

$$c_{r1} \times h + (1-e^{-\lambda h}) \times \left[p \times c_{r2} h_S + (1-p) \times c_{r2} h_L\right] \tag{1}$$

where $c_{r1} \times h$ is the cost induced by accepting the request, and $(1-e^{-\lambda h}) \times [p \times c_{r2} h_S + (1-p) \times c_{r2} h_L]$ is the cost induced by the new arriving request during h.

Similarly, the cost induced by option 2 is

$$c_{r2} \times h + (1-e^{-\lambda h}) \times \left[p \times c_{r1} h_S + (1-p) \times c_{r1} h_L\right] \tag{2}$$

The difference of these two costs ((1)–(2))is:

$$(c_{r2}-c_{r1}) \times \left\{\left[p \times h_S + (1-p) \times h_L\right] \times (1-e^{-\lambda h}) - h\right\} \tag{3}$$

We find that when the arriving request is a long request, $h=h_L$, the value of (3) is always non-negative [8]. This means that the arriving long request should always be routed to the route with the least cost (direct route mostly). Thus, we only need to focus on the case in which the arriving request is a short request. We let T denote the overall traffic volume from node *O* to *D* (Figure 1) ($T = \lambda_L \times h_L + \lambda_S \times h_S$).

However, the above analysis is just about one single vacating action, rather than the performance of overall vacating actions. To find out the cost difference between LLR and the overall vacating actions, we need to make two fixedness assumptions as follows.

Keeping the overall traffic volume, T, fixed, while holding time ratio, x, and the traffic mix, y, can be varied, for each single vacating action, we assume:

- *the value of* $(c_{r2}-c_{r1})$ *is fixed;*
- *the percentage of short requests taking vacating actions, denoted by v, is also fixed. v is computed as* $\frac{\textit{number of short requests taking vacating actions}}{\textit{number of short requests offered}}$.

Letting $h=h_S$ and substituting the definition of x in (3), we have the cost difference for ONE single vacating action started by a short request as:

$$(c_{r2}-c_{r1}) \times h_S \times \left[(1-e^{-\lambda h_S}) \times x \times (1-p) - 1\right] \tag{4}$$

Then, based on the above two Fixedness assumptions, and substituting the definitions of *x, y, T* in, the OVERALL cost difference in unit time becomes:

$$\begin{aligned} &(\textit{arrival rate of short requests}) \times v \times \textit{Equation}\ (4) \\ &= \underbrace{T \times v \times (C_{r2}-C_{r1})}_{\textit{condition}\ 1} \times (1-y) \times \underbrace{\begin{bmatrix} (\frac{y}{1-y+y/x}) \times \\ (1-e^{-(1-y+y/x) \times T}) - 1 \end{bmatrix}}_{\textit{condition}\ 2} \end{aligned} \tag{5}$$

Thus, if the vacating wants to outperform LLR, the value of (5) must be positive. In addition, the bigger the cost difference, the more effective the vacating will be.

We notice that (condition 1) >0 is generally true. This is due to $T > 0,\ 0 < v < 1,$ and $(c_{r2} - c_{r1}) > 0$. The value of condition 1 will have a direct impact on the amplitude of the cost difference. We also notice that condition 2 includes the traffic mix, holding time ratio and *Pr[one long request arrives during the holding time of a short request]*. It thus gives the tradeoff of these parameters, which is exactly the condition that ensures (5) positive. To find out this condition, we draw the curves of (5) with varied traffic mix and holding time ratio in Figure 2.

Clearly, Figure 2 shows that:

- There is an effectiveness range for vacating, around 60% ~99% in traffic mix. The maximum value occurs around 85% in the traffic mix, while the minimal negative cost difference is located at 0%. Beyond the range, the cost difference is negative, which means that the vacating idea is less efficient than LLR+TR.
- As the holding time ratio increases, so does the cost difference. But the increase in the cost difference seems to become saturated when the holding time ratio is big enough.

We now precisely define the vacating as follows: when the bandwidth utilization on a direct route reaches a certain level, the arriving short requests should be allocated to the two-hop routes instead of the direct one, so that more future arriving long requests can take the direct route instead of the two-hop routes. This kind of vacating can be called preventive-vacating, preventing long requests from two-hop-alternating.

There could be another type of vacating, called preemptive-vacating. In preemptive-vacating, the vacating is started by long request flows in contrast to preventive-vacating, which is started by short request flows. Preemptive-vacating always allocates the flows to the least loaded route, that is to say, the direct route in general. The preemptive-vacating happens when a long request flow arrives and finds the direct route fully busy. At this time, a suitable in-progress short request flow on the direct route is chosen, preempted (not interrupted but re-routed), and moved to a two-hop route. The vacated bandwidth on the direct route is then occupied by the arriving long request flow.

Obviously, the preemptive-vacating could be considered as an ideal scenario of preventive-vacating, illustrated by maximizing (3) through $(1 - e^{-\lambda h}) = 1$ and $p = 0$. In addition, we can deduce the effective range for preemptive vacating is the full range in traffic mix. We do not present the details here due to lack of space. (please reference [8] for details.)

B. Proposed Routing Schemes

Before giving a precise description for our proposed state-dependent routing schemes, we must define several concepts:

- Idle capacity: the idle capacity of a link is defined as the amount of link bandwidth that is currently not in use. We define the idle capacity of a route as the minimum idle capacity of all of its links.
- QoS-permissibility: a route, direct or two-hop, is said to be QoS-permissible if it has sufficient idle capacity to carry the request.
- TR-permissibility: a two-hop route is said to be TR-permissible if its idle capacity minus the trunk reservation threshold is greater than or equal to the requested equivalent bandwidth of the incoming request. Note that if a two-hop route is TR-permissible then it is also QoS-permissible.
- Preemption-permissibility: a preemption-permissible short request is defined as an in-progress and not-alternately-routed short request on the direct route. (i.e. the source and destination nodes of the short request are connected by this direct route.)

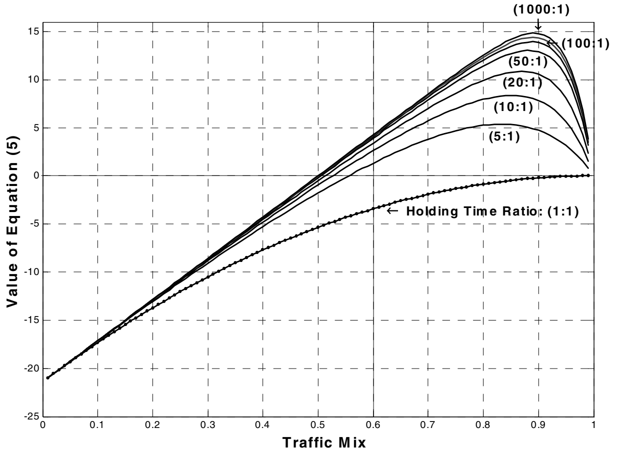

Figure 2. Curves of Equation (5) vs. traffic mix & holding time ratio

<u>Preventive-vacating routing (PVV) scheme</u>

When a new long request arrives,

- Follow the LLR+TR routing scheme

When a new short request arrives,

1. Route this short request to the direct route if idle capacity of the direct route is greater than vacating threshold. Otherwise, go to step 2.
2. If there is at least one TR permissible alternate route, route this short request to a TR-permissible alternate route with the largest idle capacity. Otherwise, go to step 3.
3. Block the short request if the direct route is not QoS-permissible. Otherwise, Route this short request to the direct route.

Note: The vacation threshold is generally less than the TR threshold. It could be, for instance, the last bandwidth unit (Figure 3). In other words, the TR first reserves the link for direct traffic (both short and long requests). In a second step, the vacating threshold reserves the link only for long requests. Besides, the terms call, flow, connection, request are interchangeable in this paper.

Preemptive-vacating routing (PEV) scheme

When a new short request arrives,

- Follow the LLR+TR routing scheme

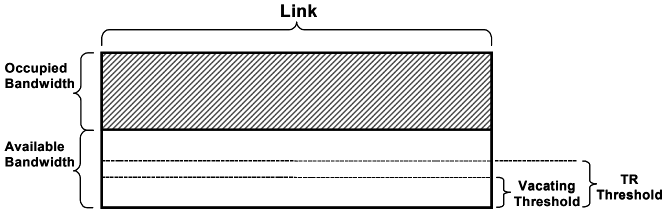

Figure 3. The link, Vacating Threshold and TR Threshold

When a new long request arrives,

1. Route this long request to the direct route if the direct route is QoS-permissible. Otherwise, go to step 2.
2. If no TR-permissible alternate routes are available, then the arriving long request is rejected. Otherwise,
   - *If there is at least one preemption-permissible short request on the direct route, then start the vacating action: preempt a randomly-selected preemption-permissible short request from the direct route to a TR-permissible alternate route with the largest idle capacity. Then, route the long request to the direct route.*
   - *If there is no preemption-permissible short request on the direct route, then route the long request to a TR-permissible alternate route with the largest idle capacity.*

LLR+TR scheme is defined as follow:

1. An arriving request, whether long or short, is routed to a direct route if the direct route is QoS-permissible. Otherwise, go to step 2.
2. If no TR-permissible alternate routes are available, then the arriving request is rejected. Otherwise, the request is routed to a TR-permissible alternate route with the largest idle capacity, i.e. the least loaded.

Restricted Access Routing (RAR)

As a variation of PVV, RAR scheme changes the step 3 of PVV to "Block the short request". Thus, in RAR, a certain amount of capacity on the direct route is reserved only for the long requests and the short requests have no right to access this portion of bandwidth.

IV. APPROXIMATED LEAST COST ROUTING

In vacating routing, we only use the concept of cost rate. We now deduce an approximated expression for the cost rate.

A. Expression for Cost Rte

Based on Hwang's work [2] (MDP approach) of state-dependent routing in multi-service networks, we obtain: (see [8] for details)

Describe the link state of link l, i, by the number of busy bandwidth units. The state-dependent cost rate of adding a long or short request at link state i, $C_r^l(i)$, can be computed as

$$c_r^l(i) = \frac{r_L^l \lambda_L^l + r_S^l \lambda_S^l}{\rho_L^l + \rho_S^l} \times \frac{E(\rho_L^l + \rho_S^l, N^l)}{E(\rho_L + \rho_S, i)}, \quad 1 \le i \le N^l \tag{6}$$

Notation: (k is L or S)

- *r_k^l: the link average reward of accepting a class k call on link l. (while r_k is the reward of accepting a class k call.)*
- *λ_k^l: the offered arrival rate of class k calls on link l.*
- *N^l: the capacity of link l.*
- *E(,): Erlang-B formula.*
- *ρ_k^l: the offered traffic intensity of class k calls on link , and is computed as $\lambda_k^l \times h_k$.*

Hence, the cost of accepting a long or short request at state i in link l is:

$$c_r^l(i) \times h_L, \text{ or } \quad c_r^l(i) \times h_S, \quad 1 \le i \le N^l \tag{7}$$

According to the route cost separability assumption [2], the cost of accepting a call on a route, *route_cost*, is the sum of the costs on each links along the route. Additionally, $route\_net\_gain = r_k - route\_cost$, *k is L or S, and* r_k *is the overall reward of accepting a class k call.*

B. Routing Scheme (A-LCR)

When a new request, whether long or short, arrives,

1. Compute the largest *route_net_gain* among all the routes;
2. If the largest *route_net_gain* is positive, allocate the request to the route with the largest *route_net_gain*; otherwise, block the request.

C. Reward Parameters

In this study, since only the holding time is heterogeneous and the network is well-engineered, we use a simple reward distribution rule according to [2], just like the one in telephone networks. That is, $r_k = r_k^l$, k is L or S.

Besides computing cost, another important advantage of reward parameters is that a flow control mechanism is automatically provided by the A-LCR scheme. This flow control mechanism is also self-adaptive. Thus, through simply adjusting the value of r_k (k is L or S), one can control the Grade of Service (GoS, i.e. blocking rate) of either long requests or short requests easily.

V. NUMERICAL RESULTS

We use computer simulations to evaluate the routing schemes we proposed for MPLS-based IP networks with heterogeneous holding time traffic. Firstly, simulation results are used to verify both the effectiveness of our schemes and the correctness of our analytical results. Secondly, we compare our schemes with other dynamic schemes thoroughly. Lastly, we demonstrate the special flow control mechanism of our A-LCR routing scheme.

The performance study is based on two network examples with: a fully connected 4-node network and a practical 12-node network (generated using Kruithov's method) (Table I). The traffic follows the system model defined in Section II. Through random number generators, the traffic mix is set to be similar across the origination-destination pairs in the network. We must say that all the simulation results in the 4-node and the 12-node network are in accordance with each other.

TABLE I. CONFIGURATION DATA FOR TWO NETWORK EXAMPLES

	4-Node Network	**12-Node Network**
Number of nodes	4	12
Bandwidth Unit (BU)	20kB	20kB
Number of single-way links	12	76 (55~101 BU)
Capacity of each link (N)	1020kB=51 BU	100MB=5k BU
Connection ratio	100% (fully connected)	60%
Fully Symmetrical	Yes	No
Nominal Total Traffic (Erlang)	529	4k
Overload Conditions	+10%	+15%

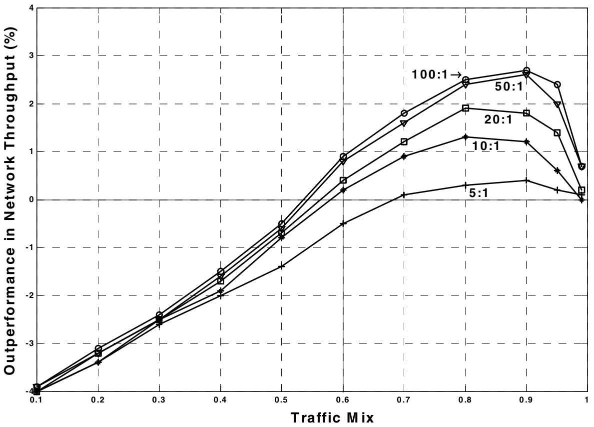

Figure 4. Outperformance of Preventive-vacating scheme compared to LLR+TR in overload traffic condition. TR threshold=3%, vacating threshold=2%. 12-node network.

A. Effective Range of Vacating

Simulation results for PVV and LLR is shown in Figure 4. As can be seen, the outperformance curves of PVV are matched very well with the curves of the cost difference obtained from Equation (5) (Figure 2), both in the amplitude and in the trend of curves. Indeed, this has confirmed the correctness and exactness of our analytical framework in Section 3 in general. Both the analytical and simulation results indicate that the effective range of PVV is around 60% ~99% in traffic mix, with maximal outperformance occurring around 85%. And there is also the "saturation" phenomenon just as in Figure 2. For PEV, its effective range is the full range of traffic mix (Figure 5).

B. Thorough Comparison

We then give a thorough comparison of the dynamic routing schemes within the heterogeneous holding time traffic environment in Figure 5 and Table II.

We find that the re-routing scheme (RER) [11] always provide a performance (in network throughput) superior to that of any other routing scheme in all the simulations, just like what it does in homogeneous networks (telephone networks) [10,11]. It can be believed that the network throughput achieved by the re-routing scheme is viewed as an upper bound for the other routing schemes. Compared with PVV, PEV has a much better performance in terms of network throughput within the full range of traffic mix. This is because that PEV is the ideal scenario of PVV. A-LCR shows its good performing in the network throughput, which is almost independent of traffic mix. RAR performs better (not too much) than PVV within the similar effective range in traffic mix. However, this is at the price of losing the fairness of routing scheme. In RAR, short requests have much higher blocking rate than that of long requests, which is just contrary to Diff-SDR. In general, our vacating schemes perform, which take into consideration the holding time for routing decisions, perform better than LLR+TR, which does not.

Regarding Diff-SDR, we notice it outperforms LLR+TR in a much narrower effective range compared with PVV and RAR. Even in this narrower range, its performance (network throughput) is similar to PVV and RAR. As holding time ratio increase, the performance of Diff-SDR is almost unchanged. Moreover, Diff-SDR has a narrower effective range in traffic loads [8]. Therefore, in Table 2 (Network Throughput row), we put Diff-SDR at the bottom (No.6) of all the six routing schemes. Through our study, we believe that the Diff-SDR is actually a special form of trunk reservation applied in heterogeneous traffic environment.

Please note that we use a factor of 10 to distance the average holding time (Figure 2,4,5]. This is only because we want to show that the holding times of long and short requests are different at least one order of magnitude. From our simulation results, it is known that this is the necessary condition for our vacating routing scheme being effective. And the larger the difference, the bigger outperformance of our vacating schemes compared to LLR+TR will be.

C. Flow Control Mechanism of A-LCR

As we can see in Figure 6, the reward parameters provide a mechanism for controlling the ratio of the long request blocking rate to the short request blocking rate over a very wide range, including their equalization. Additionally, network throughput maximization is achieved if the normalized reward parameters, $r_k^{'}$ ($r_k^{'} = r_k \times \mu_k$, k is L or S), equal each other ($r_L^{'} = r_L \times \mu_L = r_L^{'} = r_S \times \mu_S \approx 1.0$).

VI. CONCLUSIONS

The great diversity of emerging services in modern IP networks makes it possible to categorize the traffic according to their mean holding times. Actually, the categorizing work can be done only in the routing control part of the networks and would be based on the long-term statistics of the traffic. It is not necessary for final customers to know this. For instance, IP calls and IP conferences can be put in two different categories, because their average holding times (based on the long-term statistics) are different widely. They are distinguished only by routing control program of the systems, and then our protocols proposed routing schemes (PVV, PEV, RAR, etc.), which are the modifications/extension of LLR+TR technique, should be applied on them automatically. Regarding the possible practical implementation, [3] and [26] can be good references.

The main significant results we obtained in studying dynamic routing with heterogeneous holding time traffic are:

- We have found out the effective range in traffic mix is [0.60, 0.99], within which our vacating schemes outperform the traditional LLR+TR in terms of network throughput. To our knowledge, the similar thorough work has never been done in the studies of routing with multi-rate traffic.
- We derived an approximated MDP-based lease cost routing scheme, which shows its particular flow control mechanism, in addition to its constant outperformance compared to LLR+TR.
- The routing schemes we proposed perform better than the differentiated shortest distance routing (Diff-SDR) scheme, which is the only currently published dynamic routing scheme addressing the question of heterogeneous holding times.

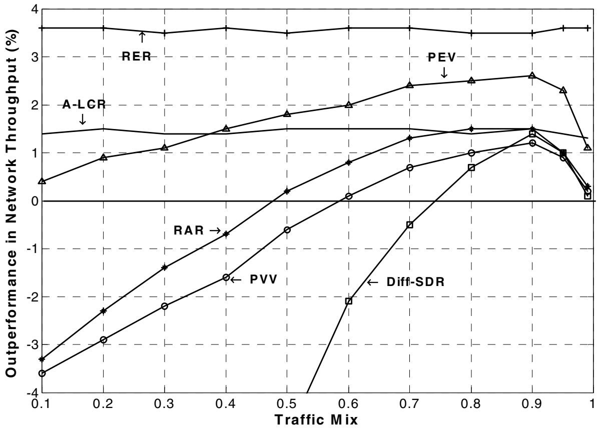

Figure 5. Outperformance (in network throughput) of all the proposed routing schemes compared to LLR+TR in the 12-node network. The holding time ratio is 10. Overload traffic condition. The TR threshold in LLR+TR, PVV, PEV, and RAR is 0.03. The vacating threshold in PVV is 0.02. The Restricted Access Threshold in RAR is 0.02

TABLE II. THOROUGH COMPARISON OF ALL ROUTING SCHEMES

Item	PVV	PEV	A-LCR	RER	RAR	Diff-SDR
Network Throughput	No.5	No.2	No.3	No.1	No.4	No.6
Fairness	Good	Good	Good	Good	Bad	Bad
Effective Range	Medium	Full range	Full range	Full range	Medi-um	Narrow
Holding Time Ratio ↑	↑	↑	—	—	↑	—
TR ↑ (impact on performance)	↑	↑↓*	—	↓	↑	—
TR ↑ (impact on outperformance)	↓	↓	↓	↓	↓	↓
Implementation	Easy	Not easy	Medi-um	Not easy	Easy	Medium

Note 1: “—” means there is no impact.

Note 2: regarding the impact of TR on the performance of PEV, within the effective of vacating, increasing the TR degrades its performance slightly; while outside the effective range of vacating, increasing the TR improves its performance. Thus, it is shown as “↑↓” in the table.

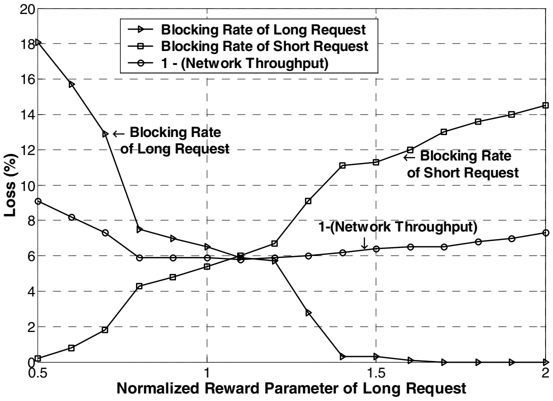

Figure 6. Traffic Loss vs. normalized reward parameter of long requests in the 4-node network in overload traffic. Traffic mix is 50%, holding time ratio is 10.

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