Path Selection Methods for Localized Quality of Service Routing

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Abstract—**Localized Quality of Service (QoS) routing was recently proposed as an alternative to the QoS routing algorithms that use global network state information to make routing decisions. In localized QoS routing, each router maintains a predetermined set of candidate paths for each of the destinations. A router decides the path for a connection request based on the information maintained locally at the router. Hence, localized QoS routing avoids the problems associated with the maintenance of the global network state information. To achieve good routing performance, localized QoS routing must effectively select the predetermined set of candidate paths. This paper studies path selection methods for localized QoS routing. Five path selection heuristics, namely breadth-first search path selection, per-pair shortest path selection, global path selection, hybrid per-pair/global path selection, and per-pair path selection with global tuning, are proposed and their performance is evaluated through simulation. We conclude that path selection methods can greatly affect the performance of localized QoS routing and that an effective path selection algorithm must consider various factors, including path length and load balancing in the whole network.**

I. INTRODUCTION

Quality of Service (QoS) routing identifies paths that meet the QoS requirement of a connection and selects the one that leads to high overall resource efficiency. Most of the existing QoS routing algorithms rely on the global network state information to make routing decisions [1], [2], [3], [7], [8]. Such algorithms will be called *global QoS routing algorithms*. Global QoS routing algorithms require the global network state information to be exchanged periodically using either the link state algorithm [5] or the distance vector algorithm [4]. For such algorithms to be effective, the global network state information must be precise and the maintenance of the global network state information may incur large overheads in both communication and CPU processing.

The localized QoS routing scheme [6] attempts to overcome the problems associated with the maintenance of the global network state information by making routing decisions based solely on the information maintained locally at each router. In the localized QoS routing scheme, each router has a predetermined set of candidate paths to each of the destinations. The source node infers the network QoS state based on the information collected locally, such as the flow blocking probability, and selects a path from the predetermined set of candidate paths for a connection request. In this paper, we will use the words *flow* and *connection* interchangeably.

While it has been demonstrated that localized QoS routing is simple, stable, adaptive and effective in comparison to global QoS routing schemes [6], a number of issues remain to be addressed. How many candidate paths do we need to have for each pair of nodes? How to select the candidate paths? Since the predetermined sets of candidate paths govern how the localized QoS routing algorithm works, it is crucial to select "good" candidate paths for the routing algorithm to achieve good performance. These important issues were ignored by the previous study [6] where an ad hoc method was used to select candidate paths. This paper fills in the gap by studying path selection schemes that systematically determine candidate paths for a given network.

In this paper, we study various path selection heuristics. Each method focuses on different factors, such as path length and global load balancing, that can affect the routing performance. By studying these heuristics, we hope to determine which factors are more important and which factors are less critical and to find an efficient way to perform path selection for localized QoS routing. We analyze static measurements of the paths selected by the heuristics and perform extensive simulations to compare the performance of the heuristics. Our main conclusions include the followings. First, path selection methods can greatly affect the performance of localized QoS routing. Second, localized QoS routing with multiple candidate paths between each source-destination pair performs better than that with only one path between each source-destination pair. Third, in order for localized QoS routing to be effective, only the paths whose lengths are close to the minimum-hop (between the source and the destination) should be selected as candidate paths. Fourth, global load balancing is an important factor in the path selection process.

The rest of the paper is structured as follows. Section 2 introduces a localized QoS routing algorithm, proportional sticky routing, which is the only localized QoS routing algorithm proposed. We evaluate the path selection schemes using this algorithm. Section 3 describes the path selection heuristics. Section 4 studies the performance of the heuristics. Section 5 concludes the paper.

II. LOCALIZED QOS ROUTING

In this section, we will describe a localized QoS routing scheme, *proportional sticky routing* (*psr*) [6]. Our path selection schemes are developed for this algorithm.

In the *psr* scheme, it is assumed that each node has a predefined set of candidate paths to each of the destination nodes. For each connection request, *psr* selects a path in the predefined set based on the flow blocking probability. The *psr* scheme can be viewed to operate in two stages: proportional flow routing and computation of flow proportions.

Psr proceeds in *cycles* of variable lengths. A number of cy-

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cles form an *observation period*. During an observation period, paths are selected based on the *flow proportion* parameter associated with each candidate path. The information of the flow blocking probability for each candidate path is collected. At the end of the observation period, a new flow proportion for each path is computed using the flow blocking probability information. Paths with lower blocking probability will have larger flow proportions.

Given the flow proportion, *psr* works as follows. During each cycle, incoming flows are routed along paths selected from a set of *eligible* paths. Initially, all the candidate paths are eligible paths. Each candidate path is associated with a variable called maximum permissible flow blocking parameter, which determines how many times this path can block a request before the path becomes *ineligible*. The maximum permissible flow blocking parameter may be dynamically adjusted to adapt to network conditions. When all paths become ineligible, a cycle ends and all parameters are reset to start the next cycle. The probability that an eligible path is selected for a flow depends on its flow proportion. The larger the flow proportion, the larger the probability.

The *psr* scheme maintains self-adaptivity by controlling the number of flows routed along a path in each cycle using the maximum permissible flow blocking parameter and by re-adjusting flow proportions after every observation period. Although *psr* adds some intelligence into determining which path to use for a given connection request, the pre–computed set of paths determines the candidate paths to choose from in the first place. Thus, it is critical to select the paths in the pre–computed set effectively.

III. PATH SELECTION METHODS

This section will present path selection algorithms that determine the set of candidate paths. In the path selection process, a number of factors need to be considered:

- *Path length*. As discussed in [3], QoS routing algorithms that favor shorter paths yield better routing performance. This factor implies that the shortest path algorithm is a good algorithm to select the candidate paths.
- *Load balancing*. Since the set of candidate paths is predefined, carefully selecting the paths to evenly distributed the load will result in good performance. Load balancing must be done in the global scale, that is, the aggregate effect of all candidate paths on all links in the network must be considered.
- *Shared links*. For a given source-destination pair, multiple candidate paths are to be selected. We should minimize the number of shared links in the candidate paths for a given source-destination pair so that *psr* can be adaptive to the network state. Essentially, when a link is under heavy load, *psr* should select other paths that do not use the link for connection requests.

An efficient path selection scheme should optimize all these factors. In practice, however, compromises must be made. In the following, we will present a number of path selection heuristics, which focus one or more of the factors while ignoring others. Five path selection heuristics will be described. We assume that the network load is uniform and all links have the same bandwidth for simplicity. The heuristics can be modified to handle non-uniform traffic and un-even link bandwidth. We also assume that the QoS metric is bandwidth and that all links in the network can satisfy the QoS requirement.

Breadth first search path selection *(BFS)*

This heuristic focuses on selecting shortest paths between as candidate paths. For each source-destination pair, the heuristic uses a breadth first search algorithm to find *all* minimum-hop paths, as well as some alternative paths with a limited extra path length. It then selects from the found paths the set of candidate paths. This heuristic ignores the global load-balancing and shared link issues.

Per-pair path selection *(PP)*

This heuristic attempts to find shortest paths between each source-destination pair while minimizing the number of shared links in the candidate paths for a given source-destination pair. This heuristic selects candidate paths for each source-destination pair in the following manner. It initially assigns the same weight, 1, to all links in the network and use the Dijkstra shortest path algorithm to find the first candidate path. After the heuristic finds a candidate path, it increases the weights on all the links along the path and then repeats the process until the number of candidate paths reaches the target or no more new paths can be found. By increasing the weights for the links in the selected paths, the heuristic tends to avoid using the links that are in the selected candidate paths and thus, minimize the number of shared links in the candidate paths. However, this heuristic does not consider the global load balancing issue.

Global path selection *(GP)*

GP selects paths for all source-destination pairs such that the load is evenly distributed to all links. This is done as follows: GP first assigns the same weight, 1, to all links in the network. GP then considers each pair of nodes in a round-robin fashion. For the first pair of nodes, GP selects one shortest path using the Dijkstra shortest path algorithm and increases the weights on the links along the path. It does the same for the second source-destination pair and so on. Since the weights of the links on the paths chosen previously have been increased, it is likely that the links in the selected paths will not be chosen in the future. Since GP considers all source-destination pairs, it is likely that the load on all links will be balanced at the end of the path selection process.

Hybrid per-pair/global path selection *(PPGP)*

This heuristic tunes the path selection process of GP. The idea is to include at least one shortest path in the candidate path for each source-destination pair while balancing the global load. In PPGP, we first use the PP to select one path for each source-destination pair. The paths selected by PP are minimum-hop paths. We then assign the weights according to the network load and find alternative paths using the global path selection method.

Algo.	Path Length	Load Balancing	Shared Links
BFS	Yes	No	No
PP	Yes	No	Yes
GP	Yes	Yes	Yes
PPGP	Yes	Yes	Yes
PPGT	Yes	Yes	Yes

TABLE I
SUMMARY OF THE HEURISTICS

PP with global tuning *(PPGT)*

PPGT tries to achieve global load balancing using a different approach. In this heuristic, we first select the set of candidate paths using PP. Since PP does not take global load balancing into consideration, it is possible that the load on some link is much higher than the load on other links. Thus, the heuristic tries to balance the load by removing paths that use the most loaded links. The process is repeated until no more paths can be removed, that is, the number of paths between each source-destination pair is below a target value. In this heuristic, if we want to find x paths between two nodes, we will first use PP to find $2x$ paths and then start the removing process.

Table III summarizes the heuristics. Among these path selection methods, BFS considers only path length. PP takes both path length and the reduction of shared links into consideration. GP, PPGP and PPGT consider all the three factors with different emphases. Two parameters are incorporated into all the heuristics, the *maximum number of paths between two nodes* and the *extra path length*. The maximum number of paths parameter controls the number of candidate paths to be found. The extra path length parameter is incorporated into the heuristics so that the heuristics will only find paths that are within the extra path length of the minimum hop path. In other words, the lengths of all candidate paths found by the heuristics are less than minimum-hop plus the extra path length parameter.

IV. PERFORMANCE STUDY

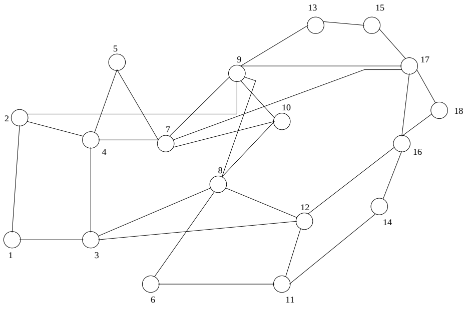


Fig. 1. The ISP topology

This section evaluates the performance of the proposed path selection algorithms. In this study, we use the same simulation environment as that used in [6]. Figure 1 shows the *isp* topology used in the study. All the links are assumed to be bi-directional 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 flow dynamics of the network are modeled as follows. 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 set of all nodes except the source node. The holding time of a flow is exponentially distributed with mean $1/\mu$. The offered network load is given by $\rho = \lambda N h'/\mu LC$ where N is the number of source nodes, L is the number of links and h' is the mean number of hops per flow, averaged across all source-destination pairs. The parameters used in this simulation are $C = 20$, $N = 18$, $L = 60$. $h' = 2.36$ and $1/\mu = 60$ seconds. The average arrival rate at a source node λ is set depending upon the desired load. In *psr*, 3 cycles form an observation period and the maximum permissible flow blocking parameter is initially set to 5.

A. Static measurements

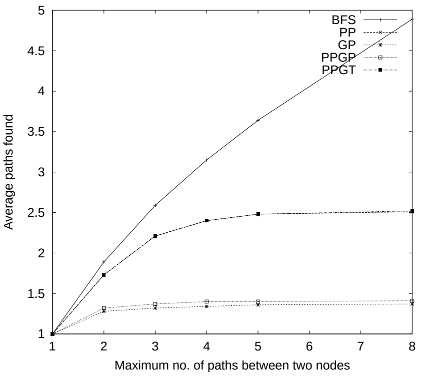


Fig. 2. The average number of paths between a source and a destination

We first examine the static measurements of the paths selected by the heuristics. Figure 2 shows the average number of paths found using each of the heuristics. In this experiment, the extra path length is assumed to be 1 if the minimum-hop between the source and the destination is less than or equal to 2, and 2 if the minimum-hop is more than 2. The x-axis is the maximum number of paths between two nodes. The y-axis is the average number of paths actually found by the heuristics. This figure shows the capability of each heuristic to find different paths between a pair of nodes. As can be seen from the figure, the average number of paths found by BFS grows almost linearly with the maximum number of paths, which indicates that BFS can found many different paths. PP and PPGT find on average around 2.5 paths even when the maximum number of paths between two nodes is 8. GP and PPGP are the worst in terms of finding different paths. They can only find an average of 1.4 paths between two nodes since they repeatedly select the same candidate paths and are unable to find other potential candidate paths.

Figure 3 shows the average path length for all the paths found using each of the heuristics with the same experimental setting as that in Figure 2. The paths found by PPGP is the shortest, followed by GP. This indicates that the candidate paths found by PPGP and GP are mostly good quality minimum-hop paths although these two heuristics cannot find many candidate paths.

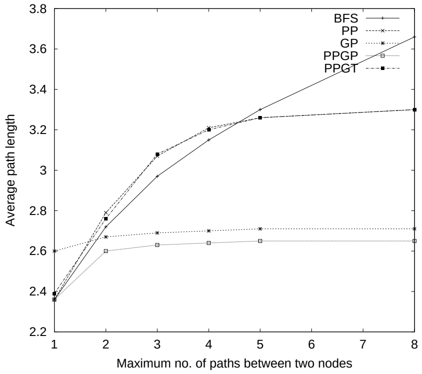


Fig. 3. The average path length

When the maximum number of paths is less than 4, BFS is better than PP and PPGT. When the maximum number of paths is larger than 4, BFS results in the largest average path length. The reason is that BFS can find more paths, including both minimum-hop paths and alternative paths. When the total number of paths between a pair of nodes is small (< 4), BFS will mostly select minimum-hop paths as candidate paths. When the total number of paths is large (> 4), more alternative paths will be included, resulting in a larger average path length.

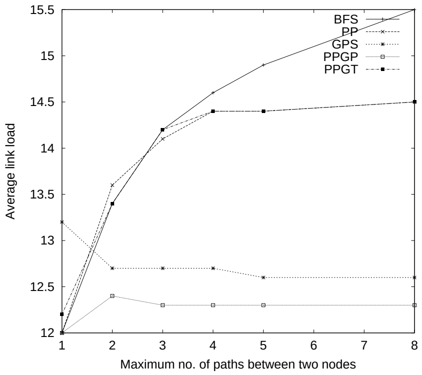


Fig. 4. Average link load

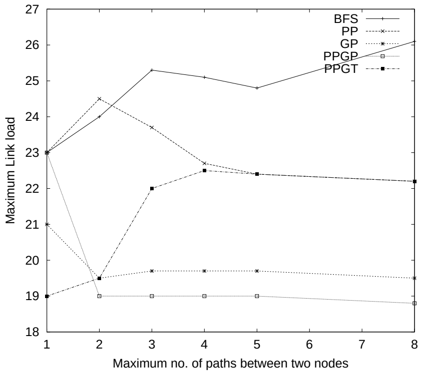
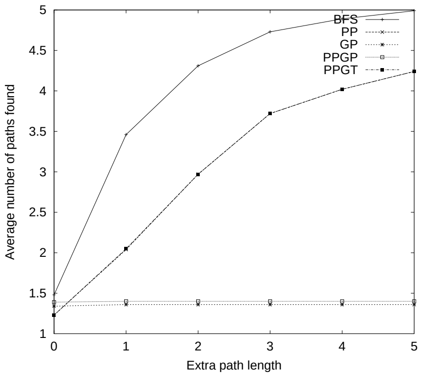
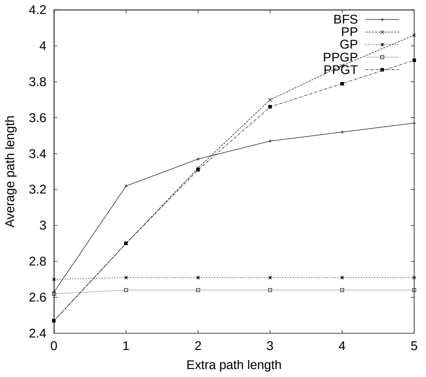


Fig. 5. Maximum link load

Figure 4 shows the average static link load and Figure 5 shows the maximum static link load using the same experimental setting as that in Figure 2 and Figure 3. The static link load is computed by assuming that there is 1 unit of data flowing between each pair of nodes and the unit is evenly distributed on all paths between the pair of nodes. When the maximum number of paths between two nodes is larger than 2, GP and PPGP have lower average load in comparison to BFS, PP and PPGT. This is because GP and PPGP tend not to select alternative paths as candidate paths while BFS, PP and PPGT select alternative paths as candidate paths. Comparing PP and PPGT, we can see that when the maximum number of paths between two nodes is small (< 5), PPGT yields lower average link load by considering the global load balancing issue.



(a) Average number of paths



(b) Average path length

Fig. 6. Static measurements for different extra path lengths

Figure 6 shows the average number of paths found and the average path lengths for different extra path lengths, assuming that the maximum number of paths per pair of nodes is 5. BFS. The results show that BFS, PP and PPGT can find more paths when a larger extra path length is allowed while GP and PPGP do not have this ability. This indicates that GP and PPGP only find good paths. BFS, PP and PPGT can find more paths with longer path lengths.

Since many factors can affect the routing performance, the static measurements do not give a clear picture about the heuristics. On the one hand, BFS finds more paths than other heuristics, which allow the localized routing algorithm to be more

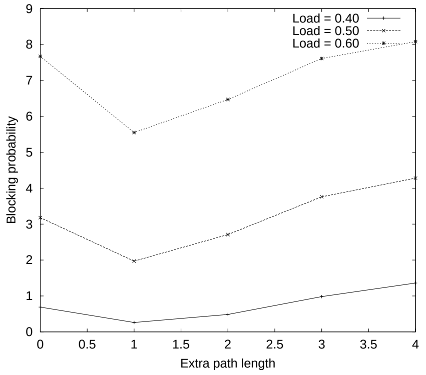


Fig. 7. Impact of the extra path length on PP

adaptive. On the other hand, the paths found by BFS are longer than those found by other heuristics, which can result in higher network load and degrade the performance. GP and PPGT cannot find many paths. Yet the paths found by these two heuristics are shown to be of high quality. The next section studies the overall effects by comparing the dynamic measurement of the blocking probability for all the path selection algorithms.

B. Dynamic measurements

We first consider the impact of the extra path length parameter. Figure 7 shows the impact on PP. The impact on PPGT and BFS is similar to that on PP, In this figure, the maximum number of paths between a source-destination pair is 5. As can be seen in the figure, for PP, an extra path length of 1 to 2 results in the best performance. When the extra path length is 0, the algorithm can only select minimum hop paths as candidate paths. In this case, although the average path length is small, the number of paths between each pair is also small (as observed in Figure 6) and the self-adaptivity of *psr* cannot be exploited. When the extra path length is too large, the average path length is too long and the routing performance decreases. We have also studied the impact on extra path length on PP and PPGP. Due to space limitation, we omit the performance figure. For these two path selection schemes, the extra path length parameter does not make much difference since GP and PPGP can only select a very small set of paths as candidate regardless of the extra path length parameter as shown in figure 6. This experiment shows that in order for localized QoS routing to be effective, only the paths whose lengths are very close to the minimum-hop should be selected as candidate paths. Since the best performance is obtained when the extra path length is between 1 and 2, for the rest of the experiments, we will assume that the extra path length is equal to 1 if the minimum hop is less than or equal to 2, and 2 if the minimum hop is more than 2.

Figure 8 shows the performance of PP with different maximum number of paths for each source-destination pair. We use the legend $heuristic(maxpath)$ to denote the *heuristic* with $maxpath$ being the maximum number of paths per pair of nodes. For example, PP(2) means PP with a maximum of 2 paths for each pair of nodes. In this figure, we observe that allowing more than one path per pair of nodes performs much better than only use a path between each pair of nodes. PP(3)

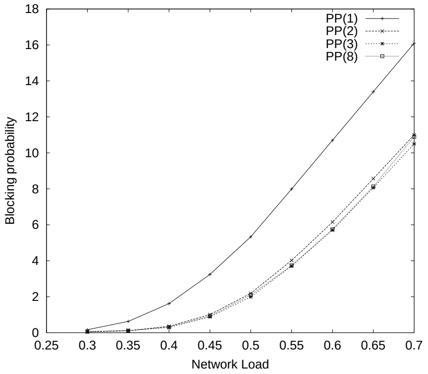


Fig. 8. PP with different maximum numbers of paths per pair of nodes

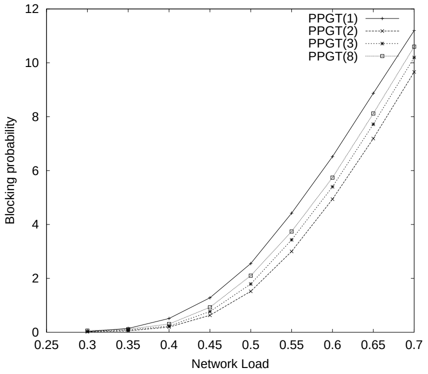


Fig. 9. PPGT with different maximum numbers of paths per pair of nodes

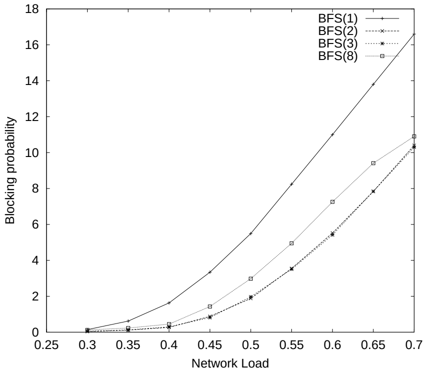


Fig. 10. BFS with different maximum numbers of paths per pair of nodes

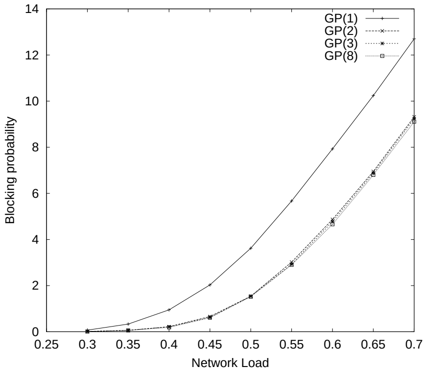


Fig. 11. GP with different maximum numbers of paths per pair of nodes

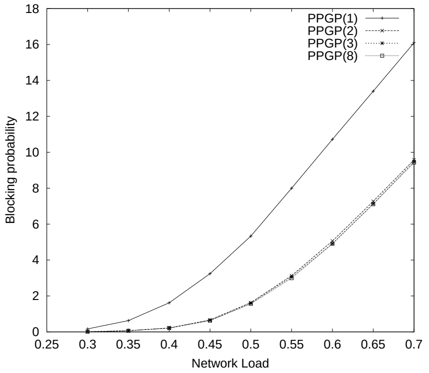


Fig. 12. PPGP with different maximum numbers of paths per pair of nodes

results in the best performance. Figure 9 shows the results for PPGT. For PPGT, allowing more paths per pair of nodes noticeably decreases the performance. PPGT(8) performs worse than PPGT(2). This indicates that when trying to select a large number of candidate paths, PPGT starts to select more alternative paths and the overall performance decreases. Figure 10 shows the results for BFS. The trend is similar to that for PPGT. Figures 11 and 12 show the results for GP and PPGP respectively. As discussed previously, GP and PPGP are not able to find many candidates, thus, allowing more paths between two nodes does not affect these two heuristics. When the number of paths between two nodes is larger than 1, the performance of the heuristics are similar. Allowing more paths improves routing performance slightly. The results in this set of experiments show that regardless of the path selection schemes, localized QoS routing needs multiple paths for each source-destination pair to be effective. The results also indicate that the optimum value for the number of paths between two nodes depends on the path selection scheme. When the path selection scheme, such as PP and PPGT, tends to find more paths at the cost of finding longer alternative paths, trying to use a large number of paths between two nodes may not be effective.

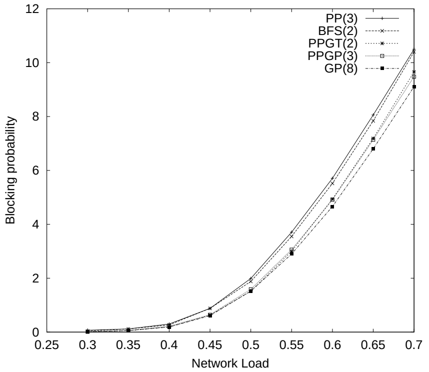


Fig. 13. Comparison of the heuristics

Figure 13 shows the comparison of all the five heuristics. We use the best maximum number of paths per pair of nodes parameter for each heuristic in the comparison. The result shows that different path selection heuristics result in difference in the routing performance. GP performs better than PPGP and PPGT which in turn perform better than BFS and PP. The heuristics (GP, PPGP and PPGT) that consider global load balancing perform better than the ones that do not consider global load balancing (PP and BFS) and the one (GP) that emphasizes on global load balancing performs better than the ones that do not emphasize on global load balancing (PPGP and PPGT). One interesting observation of this experiment is that GP perform better than PPGP. Almost all the static measurements would suggest that PPGP should perform better than GP since PPGP has shorter path length, lower average load and lower maximum load. Due to the self-adaptivity of *psr*, GP performs slightly but consistently better than PPGP.

V. CONCLUSIONS

In this paper, we investigate the path selection schemes for localized QoS routing. Five path selection heuristics, namely breadth-first search path selection, per-pair path selection, global path selection, hybrid per-pair/global path selection, and per-pair path selection with global tuning, are proposed and studied. Following are the conclusions we draw from this study.

- Although localized QoS routing has the self-adaptive capability, path selection schemes still have significant impact on its routing performance.
- Regardless of the path selection schemes, allowing multiple paths between two nodes always performs better than allowing only a single path between two nodes in localized QoS routing.
- The optimum value for the maximum number of paths between two nodes depends on the path selection scheme. When the path selection scheme tends to find more paths at the cost of finding longer alternative paths, trying to use a large number of paths between two nodes may not be effective.
- In order for localized QoS routing to be effective, only the paths whose lengths are very close to the minimum-hop should be selected as candidate paths.
- Global load balancing is an important factor in the path selection process.
- Among the five path selection schemes studied, GP, which considers three factors, path length, global load balancing and shared links, with emphasis on global load balancing, achieves the best routing performance.

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