A Comparative Study of Routing Metrics for Reliable Multi-Path Provisioning

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Abstract—We present a comparative study of routing metrics intended to optimize routing reliability and maximum link utilization (MLU) for network provisioning. The routing metrics are applied to a novel Path Indexed Linear Program (PILP) that simultaneously minimizes the MLU and maximizes the expected satisfied demand (ESD) from source nodes to destination nodes while considering a probabilistic link failure model. ESD is a performance objective that measures the expectation of the aggregate satisfied traffic demand. We additionally propose a new weighted sum routing metric that produces better trade-off solutions than those by traditional routing metrics.

I. INTRODUCTION

An important Quality of Service (QoS) objective in designing routing schemes for high-speed computer networks is reliability. Several factors can cause link failures in computer networks such as physical media cuts, natural disasters, or attacks in general. Resilience to link failures, a form of protection, is highly desirable. For example, a deterministic way for achieving flow protection against a single link failure is to provision a redundant/protection path for each main path such that the main and the protection paths do not share any links. While this allows for guaranteed failover in the case of a single link failure, it comes at a high cost. Alternatively, a probabilistic link failure model has the ability to provide acceptable resilience to link failure at a much lower cost. The objective here instead is to route traffic through the most reliable paths, where each link is assumed to fail with a certain probability (a measure of the quality of the link). Much of the work in this vein focuses on finding the single most reliable path over which the full traffic demand is routed [1], [2].

Besides reliability, traffic engineering is important to avoid congestion in the network. In networks such as MPLS and next-generation SONET/SDH supporting virtual concatenation (VCAT), network operators are concerned with setting up tunnels such that the aggregate satisfied demand is maximized while the maximum link utilization (MLU) is minimized. Aggregate satisfied demand is defined here as the total (considering all source-destination pairs) end-to-end demand successfully routed over the network. Maximizing the satisfied demand and minimizing the MLU are highly desirable to network operators as it directly affects their bottom-line. More clearly, maximizing satisfied demand results in increased infrastructure economies and in direct operational (opex) and capital expense (capex) savings. Minimizing MLU results in network load balancing which eliminates demand hot-spots and heat spikes. Load balancing decreases packet delay and reduces packet loss due to reduced queuing at the routers. Eliminating heat spikes additionally results in more efficient cooling, and enables operators to scale up their aggregate load while maintaining the same cooling infrastructure.

Recent work has explored multi-path provisioning to optimize either reliability alone [3] or both traffic engineering and reliability jointly [4]. While these previous works focus on either the maximization of the expected satisfied demand (ESD) or the the minimization of the MLU, a still open research issue is the best routing metric to satisfactorily both objectives. In this paper, we study different routing metrics to achieve this goal and propose an alternative metric that combines multiple metrics using a weighted sum. The metric is applied to a novel Path Indexed Linear Program (PILP) that simultaneously minimizes the MLU and maximizes the ESD while considering a probabilistic link failure model. The paper is organized as follows. Section II discusses related work. Section III formulates the problem and presents the routing metrics used by the PILP model. Section IV shows numerical results and Section V concludes our work.

II. RELATED WORK

K. Lee et al. [1] investigated the survivability of layered networks assuming that physical links experience random failures. Authors developed algorithms for routing which maximize reliability (survivability probability). H. Lee et al. [2] developed routing schemes for dealing with link failures. They took a probabilistic view of network failures where failure events can occur, and developed algorithms for finding diverse routes (primary and backup paths) with minimum joint failure probability. The authors formulated the problem of finding two paths with minimum joint failure probability as an Integer Non-Linear Program (INLP) and developed approximation and linear relaxation algorithms that can find nearly optimal solutions. Both approaches addressed only the routing on probabilistic failure networks. These schemes consist of single-path routing (e.g., in [2] only the primary path operates; the backup path is only activated in case of failure of the primary path) without considering link capacities (un-capacitated network).

Traffic engineering is applied to a diverse range of networks such as WDM and IP networks [5], [6], [7]. Jaekel et al. [8] presented two Integer Linear Programs (ILPs) which minimize
the MLU and the resources used to route the connection requests. A traffic engineering scheme which minimizes congestion is proposed in [9]. Our previous work [4], [5], [6], [10] includes optimization approaches for joint throughput optimization and traffic engineering. Results have showed that the simultaneous optimization of traffic engineering and throughput allows to obtain trade-off solutions. Another routing scheme where multi-objective optimization has significantly increased network performance is the routing algorithm for wireless mesh networks (WMNs) [11] known as WCETT. In WCETT, the main improvement idea is the combination of different objectives on a weighted sum. Rai et al. [3] presented two heuristics for traffic provisioning and demonstrated that multi-path routing optimizing expected bandwidth (similar to ESD) produces better results than previous approaches.

III. PATH INDEXED OPTIMIZATION MODEL AND ROUTING METRICS FOR MULTI-PATH PROVISIONING

A. Problem Formulation

We represent the network as a graph $G = (V, E)$, where $V$ is the set of nodes and $E$ the set of links. Let $N$ be the set of end-to-end flows or traffic demands. Each demand is characterized by a 3-tuple $(s_n, d_n, r_n)$, which denotes the source node, the destination node, and the rate or bandwidth needed to be allocated to traffic demand $n \in N$.

Resilience routing schemes attempt to route traffic through the most reliable paths. In single-path routing, all traffic is sent through the path having minimum failure probability. Let $p_{ij}$ be the probability that link $(i, j)$ fails, then link $(i, j)$ will survive with probability $1 - p_{ij}$. Assume independent link failures. Thus, the survivability probability of path $P$ is given by $S(P) = \prod_{(i, j) \in P} (1 - p_{ij})$ [1], [2]. This resilient routing model however does not account for link capacities [1], [2], and is hence less realistic for traffic engineering of variable demands over capacity-constrained links.

We consider a realistic capacitated network. Let $c_{ij}$ be the capacity of the link $(i, j)$. Let $P_n$ denote the set of paths from node $s_n$ to node $d_n$ for $n \in N$, and $x(P)$ the traffic routed through path $P \in P_n$. The expected satisfied demand routed through path $P$ can be defined as $E[x(P)] = x(P) \cdot \prod_{(i, j) \in P} (1 - p_{ij})$. The multi-path provision problem with traffic engineering and probabilistic failures is given in Fig. 1. The objective function $F$ consists of two terms with their corresponding weights $w_1$ and $w_2$. We define the first term as the aggregate expected satisfied demand (ESD) which is the expected traffic demand satisfied including all end-to-end flows. Note that by maximizing ESD, the model routes traffic through those paths with higher survivability probability. The second term is the MLU. Maximizing the negative of MLU is equivalent to minimizing it. Eq. (1) is the flow conservation constraint. Eq. (2) is the link capacity constraint. Eq. (3) restricts the traffic through path $P$ to be positive, and Eq. (4) states that $\alpha$ is between zero and one.

\begin{align*}
\text{Max } F &= w_1 \cdot \sum_{n \in N} \sum_{P \in P_n} E[x(P)] - w_2 \cdot \alpha \\
\sum_{P \in P_n} x(P) &= r_n \quad n \in N \quad (1) \\
\sum_{n \in N} \sum_{P \in P_n[(i,j) \in P]} x(P) &\leq \alpha \cdot c_{ij} \quad (i,j) \in E \quad (2) \\
x(P) &\geq 0 \quad n \in N, P \in P_n \quad (3) \\
0 &\leq \alpha \leq 1 \quad (4)
\end{align*}

\[\text{Fig. 1. Path Indexed Linear Program (PILP).}\]

B. Routing Metrics

The optimal solution by PILP requires listing all paths from all source-destination paths. Since in general there can be an exponential number of paths from a source to a destination, PILP has an exponential running time. Additionally, multi-constrained routing problems can be shown to be NP-complete [3]. Thus, rather than listing all paths from a source to a destination, an alternative is to implement PILP with candidate paths list [7]. Using this approach, we restrict the number of path from a source node to a destination node to the $K$ shortest paths. This approach is simple to implement by listing the paths using a ranking loopless path algorithm such as Yen’s algorithm [12]. The complexity of listing the $K$ shortest paths with such algorithm is $O(K|V|(|E| + |V|\log|V|))$. Thus, by limiting the number of paths to a reasonable size, we limit the number of variables of PILP given by Eq. (3), which permits us to solve PILP in reasonable time.

The main issue is the metric to be used to list the $K$ shortest paths. The following link metrics are the most widely used:

\begin{align*}
\text{cost}_{ij} &= -\log(1 - p_{ij}), \quad (5) \\
\text{cost}_{ij} &= \frac{k_1}{c_{ij}}, \quad (6) \\
\text{cost}_{ij} &= \frac{k_2}{c_{ij} \cdot (1 - p_{ij})}, \quad (7) \\
\text{cost}_{ij} &= 1. \quad (8)
\end{align*}

Eq. (5) quantifies reliability [1], [2]. It can be shown that the shortest path under this cost system is equivalent to the path with the highest reliability. This cost system is referred to as \textit{logarithmic probabilistic} (log-prob) cost system. In Eq. (6), $k_1$ is a constant and $c_{ij}$ is the capacity of the link. This cost system indicates that the cost of a link is inversely proportional to its capacity. This cost system is used by Open Shortest Path First (OSPF) to favor high-bandwidth links and avoid congestion. Eq. (7) is similar to Eq. (6) except that the capacity of the link is multiplied by the link availability. Finally, the cost system under Eq. (8) indicates that the cost of a link is simply one and thus the shortest path is given by the path with the minimum number of hops. Protocols such as Routing Information Protocol (RIP) versions 1 and 2 use this metric. Additionally, under the assumption of uniform failure probability in the network, the shortest-hop path may have the lowest failure probability.

Listing the $K$ shortest paths using the cost systems given by either Eq. (6) or Eq. (7) and applying the paths to PILP would favor traffic engineering and the minimization of the MLU,
because paths with high bandwidth would be included. On the other hand, listing the $K$ shortest paths using either Eq. (5) or Eq. (8) may favor the maximization of the ESD since the list would include the most reliable paths. As an alternative trade-off approach to try to balance these two conflicting objectives, we propose the following cost system:

$$cost_{ij} = -\beta \cdot \log(1 - p_{ij}) + (1 - \beta) \frac{E_1}{C_{ij}}$$

Eq. (9) is a weighted sum composed of Eqs. (5) and (6) which can be tuned by a tunable parameter $\beta$ subject to $0 \leq \beta \leq 1$. Thus the cost system presents an alternative link cost that provides a trade-off between link availability and bandwidth.

**Illustrative Example.** Consider the network of Fig. 2. Assume that all links have a capacity of 10 units. Assume also a traffic demand of 10 units from node 0 to node 4. The number over a link represents the survivability probability of that link. A traditional single-path routing scheme which sends all the traffic through the path having minimum failure probability (or maximum survivability probability) would produce the path $P_1 = 0 - 3 - 4$. Note that $P_1$ is the path with maximum survivability probability; $S(P_1) = 0.99^2 = 0.9801$. Thus, with a demand of 10 units, the expected satisfied demand is $E[x(P_1)] = x(P_1) \cdot S(P_1) = 9.801$ units, where $x(P_1)$ is equal to 10 units (because all traffic is sent through $P_1$). While this result is excellent if we only consider survivability probability, the resulting MLU performance is very poor; note that the utilization of links (0, 3) and (3, 4) are equal to 1 (thus the maximum link utilization $\alpha = 1$). On the other hand, a pure traffic engineering scheme minimizes $\alpha$ to 0.5 by evenly balancing the traffic through path $P_1 = 0 - 3 - 4$ and $P_2 = 0 - 1 - 4$. However, note that $S(P_2) = 0.99 \cdot 0.8 = 0.792$, which produces an $ESD = E[x(P_1)] + E[x(P_2)] = 8.86$ units, where $x(P_1) = x(P_2) = 5$ units. Finally, consider the solution produced by PILP with both $w_1 > 0$ and $w_2 > 0$. Such a solution avoids link (1, 4) and routes the traffic through $P_1 = 0 - 3 - 4$ and $P_2 = 0 - 1 - 2 - 4$ to produce $\alpha = 0.5$ and $ESD = E[x(P_1)] + E[x(P_2)] = 9.752$ units. Fig. 2(b) shows the objective space for the three solutions discussed in this example. Good solutions are located in the upper left corner. Note that PILP can find a solution with a performance objective vector into the upper left corner such as $(0.5, 9.752)$.

**IV. Numerical Results**

We obtained numerical results on two autonomous systems which were measured in [13] and accessible online [14]. Autonomous System (ASN) 3257 is composed of 161 nodes and 656 links, and ASN 3967 is composed of 79 nodes and 294 links. The topologies from [14] include the costs of the links among routers. A cost of a link in these topologies is considered to be inversely proportional to its capacity according to the recommended practice by vendors that implement OSPF. For a link $(i, j)$, we have assigned a link failure probability $p_{ij} \in (0, 0.1)$ or link availability $(1 - p_{ij}) \in (0.9, 1)$. Twenty end-to-end requests were randomly generated. $\beta$ in Eq. (9) was adjusted to obtain trade-off solutions.

Figs. 3(a)-(f) show the results obtained by PILP with two different number of $K$ shortest paths listed. Figs. 3(a)-(c) depict the ESD, MLU, and satisfied demand when $K = 10$, and Figs 3(d)-(f) depict the ESD, MLU, and satisfied demand when $K = 100$. The per source-destination traffic demands here were set to $r_n = 1.25$ units $\forall n \in N$. To study the behavior of PILP as the weight values $w_1$ and $w_2$ change relative to each other, we set $w_1 = 1$ (constant for all experiments) while increasing $w_2$ (axis $x$ in Figs. 3(a), 3(b), 3(d), and 3(e) illustrate these increments in a normalized manner). Figs. 3(c) and 3(d) show the satisfied demand (aggregate amount of traffic routed) as each per source-destination $r_n$ demand increases. The satisfied demand can be considered as the amount of traffic the network is able to support as the per source-destination demand increases; i.e.,

$$satisfied\ \text{demand} = \sum_{n \in N} \sum_{P \in P_n} x(P).$$

Fig. 3(a) and 3(d) show that the normalized ESD (normalized to the total traffic demand; i.e.,

$$\frac{ESD}{\sum_{n \in N} r_n}$$

where ESD is maximized by PILP when the $K$-shortest paths are listed according to the cost system given by Eq. (5). This result is not a surprise since the log-prob cost system favors reliability. However, note in Figs. 3(b) and 3(d) the poor MLU performance of this cost system. E.g., in Fig. 3(b), even when $w_2$ increases (thus PILP favors MLU instead of ESD) the MLU under Eq. (5) remains equal to approximately 0.58. On the other hand, note the trade-off solutions produced by Eq.(9); e.g., the ESD is approximately 86 % (Fig. 3(a)) while the MLU is considerably lower than that of Eq. (5) (Fig. 3(b)).

Figs. 3(c) and 3(f) illustrate the behavior of the cost systems as the per source-destination demands increase. When the traffic demands are low, the corresponding satisfied demands increase proportionally and all PILP solutions with the different cost systems operate satisfactorily. In these cases, the satisfied

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**Fig. 2.** Illustrative example. (a) Network topology. (b) Objective space.
demand is $\sum_{n \in N} \sum_{P \in P_n} x(P) = \sum_{n \in N} r_n$. As demands increase the network may not fully satisfy all the demands. The best performance here is obtained by PILP with Eqs. (6) and (7). These cost systems prefer high-capacity paths. On the other hand, solutions with Eq. (5) have poor satisfied demands. Consider again ESD, MLU, and satisfied demand jointly (e.g., Figs. 3(a), 3(b), and 3(c) together), note the good trade-off solutions obtained with Eq. (9). These solutions have high ESD and satisfied demand and low MLU. Fig. 4 shows the results for the ASN 3257. Similar conclusions can be derived here. While PILP with Eq. (5) produces the best solutions in terms of ESD alone (Figs. 4(a) and 4(d)), these solutions are poor in terms of MLU (4(b) and 4(e)) and satisfied demand (4(c) and 4(f)). For this network, the $\beta$ value used in Eq. (9) here favored ESD rather than MLU. However, an interesting observation is the fact that PILP with Eq. (9) obtained not only solutions with high ESD but also the solutions with highest satisfied demand. Clearly the weighted sum metric can achieve better solutions than traditional metrics. These encouraging results permit to conjecture that the weighted sum metric given by Eq. (9) may not only work well with PILP but also with other heuristics algorithms [1], [3] that attempt to optimize reliability while considering traffic engineering.

Fig. 5 shows the satisfied demand as each per source-destination $r_n$ increases for twenty end-to-end requests in ASN 3257. These results were generated with objective function weights $w_1 > 0$, $w_2 > 0$, and candidate paths list size $K = 100$. This figure compares solutions of Eq. (9) with varying values of $\beta$ to solutions of Eqs. (5)-(8). The results show that values of $\beta$ can be chosen to provide a solution that ranges between and can include the solutions of Eq. (5) and Eq. (6). In this set of results when $\beta = .975$ a solution exists that outperforms those obtained with any other equation.

V. CONCLUSION

We have presented a comparative study on routing metrics for reliable multi-path provisioning. Routing metrics were applied to a novel linear program that optimizes multiple objectives to provision for traffic demands between source-to-destination nodes. We have compared the performance in terms of ESD, MLU, and satisfied demand on two autonomous system topologies utilizing traditional routing metrics and a proposed weighted sum metric. Numerical results show that while a traditional log-prob cost system produces best solutions for maximizing ESD, its performance is poor in terms of MLU and satisfied demand. Another popular cost system where a link cost is inversely proportional to its
Fig. 4. Results for ASN 3257. (a), (b), (c) represent the ESD (Eq (11)), MLU, and Satisfied Demand (Eq. (10)) produced by PILP with a candidate paths list of size $K = 10$. (d), (e), and (f) represent similar results by PILP but with a candidate paths list of size $K = 100$.

bandwidth produces best solutions for minimizing MLU but performs poorly in terms of ESD. The best trade-off solutions are produced by the proposed weighted sum which takes into account both traffic engineering and ESD.

REFERENCES


