Diverse Lightpath Protection Against Correlated and Probabilistic Failures in Multi-Domain Optical Networks

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Abstract: This paper proposes a distributed lightpath protection scheme for diverse routing in multi-domain optical networks with correlated and probabilistic failures. This novel solution jointly considers traffic engineering and failure risk reduction objectives.

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I. Introduction

With growing bandwidth service demands, survivability in multi-domain optical *dense wavelength division multiplexing* (DWDM) networks is a major concern. Now various pre-provisioned protection schemes have been studied for such network settings; see [1]. For example, [2] develops a diverse path computation strategy using aggregated domain traversal state (via topology abstraction). Meanwhile [3] proposes another scheme to find two *link-disjoint* paths along the same domain sequence. Nevertheless these approaches are only designed for single link failures and hence their effectiveness will abate significantly in the presence of large multi-failure events, e.g., those caused by natural disasters or *weapons of mass destruction* (WMD) attacks. As a result the authors in [4] have proposed diverse routing risk-minimization strategies using *probabilistic shared risk link groups* (p-SRLG) models for correlated failures, albeit for single-domain networks only. However these strategies do not incorporate any *traffic engineering* (TE) concerns and cannot be applied in multi-domain settings with partial inter-domain visibility.

In light of the above, there is a growing need to develop *distributed* protection solutions for multi-domain optical networks to improve robustness against large-scale correlated/probabilistic multi-failure events. Although it is difficult to guarantee failure recovery under such scenarios, protection strategies that help reduce the risk of lightpath failure are still critical. Along these lines, this paper first introduces a realistic failure model evolved from the p-SRLG concept in [4] and then presents a novel distributed lightpath protection scheme for practical multi-domain DWDM networks, i.e., incorporating both risk mitigation and TE objectives.

II. Multi-Domain Lightpath Protection against Correlated/Probabilistic Failures

The proposed multi-domain protection solution assumes realistic distributed *generalized multi-protocol label switching* (GMPLS) network settings where *optical cross-connect* (OXC) nodes and domain *path computation element* (PCE) entities have complete knowledge of domain-internal resources, e.g., via *open shortest path first*-TE (OSPF-TE) routing instances. Meanwhile, border OXC nodes and PCE entities also have partial inter-domain visibility, as provided by hierarchical OSFP-TE link state routing (running between the border OXC nodes). The framework also assumes "all-optical" domains with full wavelength conversion at border OXC nodes, i.e., a realistic modeling of operational scenarios with regeneration and bit-monitoring at boundaries. Moreover, all setup signaling is done using the *resource reservation protocol* (RSVP-TE). Overall, this solution presents several key innovations, including 1) introduction of p-SRLG/link failure probability state into inter-domain topology abstraction, 2) development of novel lightpath-pair selection strategies to jointly consider risk and TE concerns, 3) limitation of inter-domain routing state (overheads) needed to achieve effective provisioning of diverse lightpath routes.

A. Correlated/Probabilistic Failure Model

The proposed failure model extends the p-SRLG concept in [4] for correlated/probabilistic failures in *multi-domain* (optical) networks. The requisite notation is first introduced. Consider an optical network comprising of D domains with the i-th domain having n^i OXC nodes and b^i border OXC nodes, $1 \leq i \leq D$. This network is represented as a set of domain sub-graphs, $\boldsymbol{G}^i(\boldsymbol{V}^i,\boldsymbol{L}^i)$, where $\boldsymbol{V}^i = \{v^i_1, v^i_2, \ldots\}$ is the set of OXC nodes in domain i and $\boldsymbol{L}^i=\{l^{ii}_{jk}\}$ is the set of *intra-domain* links ($1 \leq i \leq D$, $1 \leq j,k \leq n^i$) with available and maximum wavelengths λ^{ij}_{km} and Λ^{ij}_{km}, respectively. The *inter-domain* links $\{l^{ij}_{km}\}$ ($1 \leq i,j \leq D$, $1 \leq k \leq b^i$, $1 \leq m \leq b^j$) are also defined similarly. Then consider a random multi-failure event modeled as a p-SRLG, e, with an epicenter (corresponding to the most likely geographic location of occurrence) and a circular failure region. This region is modeled using a 2-dimensional Gaussian distribution, and the conditional failure probability of link l (subscripts/superscripts removed for simplicity) given event e can be derived from the cumulative distribution function with the closest distance, d_l, of the link from the epicenter as:

$$p_e(l) \;=\; 1-\mathrm{erf}(d_l/(\sqrt{2}\sigma)) \qquad (1)$$

where $\mathrm{erf}(x)$ is the well-known *error function* and σ is the standard deviation of the distribution, i.e., in distance units. Hence links located closer to the epicenter will have higher failure probabilities, and for all effective purposes the realistic failure region, i.e., "radius", of this event is given by 3σ. Finally, to model multiple correlated events, a set of p-SRLG's, $\boldsymbol{E}$, is defined. Here all events are assumed to be *mutually exclusive* with each having an occurrence probability of π_e, i.e., $\sum_{e\in E}\pi_e = 1$, $e\in \boldsymbol{E}$. Since a link can be located in multiple overlapping p-SRLG regions, a link risk vector is also defined, i.e., $\bar{\boldsymbol{p}}_l = [p_1, p_2, \ldots, p_{|E|}]$ (subscripts/superscripts removed for simplicity).

B. Topology Abstraction with Link Failure Probabilities

In order to generate a "skeleton" topology view at the inter-domain routing level, *full-mesh* topology abstraction is applied. Namely a domain is reduced to a mesh of intra-domain "abstract links" between border OXC pairs to provide aggregated domain traversal costs. Now the existing topology abstraction schemes have strictly focused on link resources [5]. However, for effective multi-domain protection it is crucial to capture multi-failure risk diversity in the "global" topology. Hence a novel "risk-aware" abstraction scheme is proposed to extract both capacity *and* failure probability (p-SRLG) information, i.e., by computing appropriate link risk vectors for abstract links. This is done by the domain PCE which computes the *k-shortest paths* (*k*-SP) between the respective border OXC nodes (of the abstract link) and then selects the path with the lowest *aggregate* failure probability, P_L, given by:

$$P_L = \sum_{e\in E}(\pi_e \cdot \max_{l^{ii}_{jk}\in L} p_e(l^{ii}_{jk})), \tag{2}$$

where $\boldsymbol{L}$ is the set of all (intra-domain) links traversed on the given shortest path. The capacity of this abstract link is then set to the bottleneck capacity of the chosen route. Meanwhile, its risk vector, $\bar{\boldsymbol{p}}$, is given by:

$$\bar{\boldsymbol{p}} = [\max_{l^{ii}_{jk}\in L} p_e(l^{ii}_{jk}),\ \forall e\in \boldsymbol{E}], \tag{3}$$

listing susceptibility to each p-SRLG. The resource/risk state updates for the abstract links are performed regularly, i.e., full-mesh abstraction with relative threshold inter-domain updates [5].

C. Diverse Lightpath-Pair Computation Strategies

Using the above abstracted state, three different multi-domain lightpath computation schemes are now proposed:

TE-Only: This scheme is a baseline for comparison purposes and does not incorporate risk state. Specifically, Suurballe's algorithm is run on the "skeleton" inter-domain topology to find diverse primary/backup *loose routes* (LR) domain sequences. To achieve better TE load-balancing, the weight of each physical/abstract link is set to:

$$\omega^{ij}_{km} = 1 / (u \cdot \lambda^{ij}_{km} / \Lambda^{ij}_{km}), \tag{4}$$

where u is a user-defined constant. If LR-pair computation succeeds, then the *most-used* (MU) inter-domain wavelength is selected and sequential RSVP-TE signaling initiated to setup end-to-end lightpaths, i.e., *explicit route* (ER) expansion along primary and then backup LR. During this phase each domain PCE performs LR expansion between respective ingress/egress border OXC nodes. In particular, Suurballe's algorithm is again used at the source and destination domains (and possibly intermediate domains traversed by both LR's) to compute diverse intra-domain routes with at least one free wavelength (MU selection). Overall, this approach delivers competitive results with lower abstraction complexity than [2], i.e., $O(N^2)$ versus $O(N^4)$ overheads for domain with N border nodes.

TE-Only Algorithm

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Pre-condition: Full-mesh topology abstraction
1. Set link weights with $\omega^{ij}_{km} = 1 / ( u \cdot \lambda^{ij}_{km} / \Lambda^{ij}_{km} )$
2. Find shortest LR-pair via Suurballe's algorithm
3. Expand LR's using distributed signaling
4. Apply Suurballe's algorithm in domains traversed
   by both LR's.
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Recursive Single-Path (RSP) Algorithm

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Pre-condition: Full-mesh abstraction with p-SRLG states
1. Set link weights with $\omega^{ij}_{km} = 1 / ( u \cdot \lambda^{ij}_{km} / \Lambda^{ij}_{km} )$
2. Find $k$-shortest LR's
3. Select primary LR with lowest $P_L = \sum_{e\in E}(\pi_e \cdot \max_{l\in L} p_e(l))$
4. Prune the primary LR and repeat Step 2 & 3 to find backup LR
5. Expand LR's, keeping the lowest aggregate failure probability
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Recursive Single-Path (RSP): This scheme leverages the risk-aware abstraction model and incorporates both TE and risk in LR lightpath computation. For each incoming request the source domain PCE first computes the *k*-SP LR's between the source and destination domains using load-balancing, i.e., Eq. (4). The inter-domain LR with the lowest aggregate failure probability across all p-SRLG events (and at least one free wavelength, MU selection) is then selected as the primary LR, i.e., akin to Eq. (2) applied at the *inter-domain* level. If this computation succeeds, then the same procedure is repeated for the backup LR over a modified "skeleton" topology with the primary LR links pruned (also abstract links). Finally sequential signaling is run to resolve end-to-end primary/backup lightpaths. Here intra-domain ER expansion also computes *k*-SP routes between the domain ingress/egress border OXC's and selects the one with lowest aggregate failure probability (and at least one free wavelength, MU selection).

Path-Pair Correlation (PPC): Since the RSP scheme does not account for correlation between primary and backup routes, it may not yield the best risk-reduced routes. Hence it is important to consider both routes in conjunction as well. Here the proposed PPC algorithm leverages risk-aware abstraction state to first compute k_1 candidate primary LR's over the "global" topology with link weights given by Eq. (4). Next, an additional k_2 link-disjoint backup LR's are computed for each of these k_1 primary LR's. From these $k_1.k_2$ candidates, the LR-pair with lowest probability *dot product* (and at least one free wavelength, MU selection) is selected. Specifically, risk vectors are formed for both primary/backup LR's (akin to Eq. (3) for intra-domain routes) and the dot product is given by:

$$dot\ \ product = \sum\nolimits_{e\in E} \pi_e \cdot \max\nolimits_{l\in L_1}\ p_e(l)\cdot \pi_e \cdot \max\nolimits_{l\in L_2}\ p_e(l) \tag{5}$$

where L_1 and L_2 are the sets of links on primary and backup LR's, respectively (and link subscripts removed). This approach tries to increase the "p-SRLG diversity" between the two LR's by avoiding high risk-correlation. Sequential signaling is also used to expand the chosen LR's, i.e., the intra-domain lightpath routes are selected so as not to yield any increase in failure probabilities in the LR risk vectors. If this is not possible, the route that yields the minimum increase in the overall dot product is chosen (with at least one free wavelength, MU selection). Also, if a domain is traversed by both LR's, the intra-domain path-pair is selected from the *k*-SP pairs between the respective ingress and egress OXC nodes by comparing the dot products. Therefore the PPC scheme incorporates objectives for both TE, via link weights in Eq. (4), and risk mitigation, via dot product in Eq. (5). Note that the chosen $k/k_1/k_2$ values can also affect TE and failure reliability performance.

Path-Pair Correlation (PPC) Algorithm

Pre-condition: Full-mesh abstraction with p-SRLG states

1. Set link weights with $\omega^{ij}_{km} = 1 / (u \cdot \lambda^{ij}_{km} / \Lambda^{ij}_{km})$
2. Find *k*-shortest link-disjoint LR-pairs
3. Select the LR-pair with the lowest "dot-product" defined as $\sum\nolimits_{e\in E} \pi_e^2 \cdot \max\nolimits_{l\in L_1}\ p_e(l)\cdot \max\nolimits_{l\in L_2}\ p_e(l)$
4. Expand LR's, selecting intra-domain route such that the dot product is the lowest.

III. Performance Evaluation

The multi-domain protection schemes are evaluated using *OPNET Modeler*^{TM} with a modified NSFNET topology (with nodes replaced by domains). All links have 32 wavelengths and lightpath requests are randomly generated between domains/intra-domain nodes with exponential holding times (mean 600 sec). For sufficient route variability, *k*=3 is chosen (along with k_1=3 and k_2=2 for the PPC scheme). Each run is averaged over 250,000 lightpath requests and over 1,000 p-SRLG failure events are randomly triggered one at a time. Meanwhile, failure scenarios are modeled by five mutually-exclusive/equiprobable p-SRLG events, i.e., $|E|$=5, with failure regions delineated by appropriately choosing σ in Eq. (1) so that the links associated with at least three nodes closest to the epicenter have failure probability greater than 0.9.

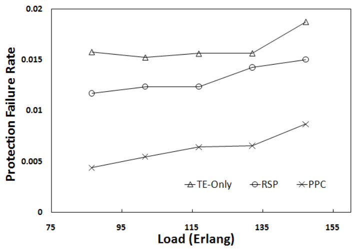

Fig.1: Protection failure rate

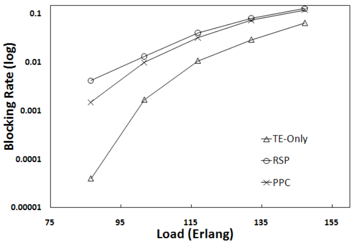

Fig.2: Lightpath request blocking rate

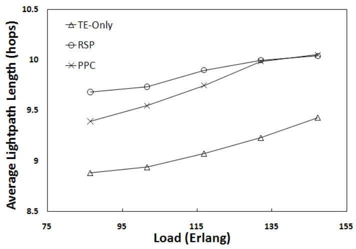

Fig. 3: Average lightpath length

Tests are first done to measure recovery performance of the schemes. Specifically, the *protection failure rate* is measured as the percentage of connections experiencing both primary *and* backup lightpath failures at the time of a p-SRLG event. The results in Fig. 1 show that the TE-Only scheme yields the highest failure rates (expected as it incorporate no risk state). Meanwhile, the PPC algorithm consistently gives the best results since the dot product operation helps increase lightpath "separation" and reduces p-SRLG overlaps in the path-pairs. By contrast the "greedy" RSP algorithm is less effective as it computes primary/backup LR's sequentially. Lightpath blocking rates are also plotted in Fig. 2. As expected, the TE-Only load-balancing algorithm gives notably lower blocking, whereas the other schemes tradeoff blocking performance to improve recovery. However, the PPC strategy still outperforms RSP, i.e., about 15% lower blocking at high loads. Finally, per-connection resource usage is gauged by measuring average end-to-end lightpath lengths in Fig. 3. Here the RSP and PPC schemes yield slightly higher utilization (about 6%-10%) as longer routes are needed to bypass potential failure regions. Overall, these results indicate the critical importance of "risk-aware" topology state and path-pair correlation in improving multi-domain protection.

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