An Optimization Approach for Multi-Domain Disaster Recovery

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Abstract: This paper develops a novel optimization scheme for multi-domain optical network protection under multiple probabilistic failures arising from large-scale disasters. The model is solved using an approximation approach and the results compared with some advanced heuristics.

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I. Introduction

Multi-domain backbone networks provide vital high-bandwidth connectivity for many new services running across wide geographic domains, e.g., such as on-line storage, content distribution, cloud, etc. As these services become more common, operators are being asked to provide a very high level of continuity, even under challenging disaster conditions. In particular, these occurrences can yield multiple spatially/temporally-correlated failures and include natural disasters, cascading power outages, and malicious *weapons of mass destruction* (WMD) attacks.

Now various pre-provisioned protection schemes have been developed for multi-domain recovery, mostly based upon heuristic designs [1]. For example, hierarchical routing is commonly used to build abstract multi-domain views and compute skeleton primary/backup paths [2],[3]. Simpler decentralized strategies have also been proposed to achieve per-domain protection [4]. However these schemes only address isolated single (node, link) failures and are problematic for large disaster-type scenarios with multiple network node/link failures. Indeed, disaster recovery under such conditions is very challenging and is compounded by limited resource visibility between domains (due to privacy and scalability concerns). To address these concerns, [5] presents a novel "risk-aware" scheme that tries to lower joint path-pair failure probabilities for pre-defined *probabilistic shared risk link group* (p-SRLG) [6] regions. However, although this solution incorporates *traffic engineering* (TE) efficiency concerns, it is still sub-optimal. Hence there is a strong need to develop more formal optimization models to bounds multi-failure performance.

In light of the above, this paper presents a novel *integer non-linear programming* (INLP) model for multi-domain disaster recovery. The solution extends upon the single-failure multi-domain protection optimization scheme in [7] by adding extensive new provisions for multi-failure p-SRLG regions. The overall optimization pursues several objectives—including throughput maximization, resource minimization, and risk avoidance—and the primary/backup routes are optimized at both the intra- and inter-domain levels, i.e., two-stage approach. This paper is organized as follows. Section II presents the hierarchical multi-objective optimization model along with a linear approximation. Section III then presents some performance evaluation results, as well as comparisons with the advanced heuristic scheme in [5]. Note that this work can also be generalized for "non-optical" bandwidth provisioning networks as well as emerging *elastic optical networks* (EON).

II. Optimization Model

A new *integer non-linear programming* (INLP) optimization is presented for multi-domain lightpath protection under multiple probabilistic failures. The framework assumes a-priori demands and pre-specified failure risk regions. The solution also models realistic hierarchical routing setups, where domain state is compressed to provide global abstract topologies. Namely, full-mesh abstraction [1],[5] is used to reduce a domain to a mesh of links between its border nodes. All domains are transparent (all-optical) but have full wavelength conversion at the border nodes. This is a valid representation as most carriers use bit-level *service level agreement* (SLA) monitoring at boundary points. Overall, the optimization uses a two-stage approach, i.e., first computing skeleton primary/backup lightpath pairs over the global "abstract" topology and then resolving them over the individual domains, Fig. 1. This hierarchical approach mimics inter-domain heuristic schemes and provides a good reference. Although it is difficult to guarantee failure recovery for all multi-failure conditions, risk mitigation is still critical. Hence the solution tries to minimize joint path-pair failures while trying to control resource usages. Consider the requisite notation first.

A backbone network is defined with D domains, with the i-th domain represented by sub-graph, $\boldsymbol{G}^i(V^i,L^i)$. Namely, here $\boldsymbol{V}^i=\{v^i_1, v^i_2, \ldots\}$ is the set of nodes and $\boldsymbol{L}^i=\{e^{ii}_{jk}\}$ is the set of intra-domain links, e^{ii}_{jk} interconnecting nodes v^i_j and v^i_k. Inter-domain links between the border nodes are also defined in the set $\{e^{ij}_{km}\}$, where $1\leq i,j\leq D$, and $i\neq j$. Using this, a global *abstract* topology is defined by the graph $\boldsymbol{H}(\boldsymbol{U},\boldsymbol{E})$. Namely, $\boldsymbol{U}=\{v^i_j\}$ is the set of border nodes in all domains and $\boldsymbol{E}=\{e^{ij}_{km}\}$ is the set of global links, i.e., both physical inter-domain links (e^{ij}_{km} between domains i and j) and *abstract* intra-domain links (e^{ii}_{jk} in domain i). Without loss of generality, intra- and inter-domain link sizes are also set to C_1 and C_2 wavelength channels, respectively. Meanwhile, the p-SRLG model from [6] is used to specify a pre-defined set of mutually-exclusive stressor events, $\boldsymbol{R}$, where each event $r\epsilon\boldsymbol{R}$ has an occurrence probability Π_r and $\Sigma_r\Pi_r=1$. Probabilistic failure regions are also defined for each stressor to model its impact regime, i.e., via non-zero conditional failure probabilities for each link e^{ij}_{km} within the geographic region of event r, i.e., p^r_{ikjm}. As per [6], it is assumed that all link failures within a region (for stressor r) are independent. Finally, all user requests are denoted by the set $N=\{(s_n,d_n,r_n)\}$, where the *n-th* request has source node s_n, destination node d_n, and requested capacity r_n wavelengths. Some other variables are also defined here. Namely, f_n denotes the number of wavelengths allocated to the n-th request, x^{nij}_{km} denotes the number of wavelengths routed over link e^{ij}_{km} for the primary path for request n, and y^{nij}_{km} denotes the number of wavelengths routed over link e^{ij}_{km} for the backup path for request n. Assuming single-wavelength requests, i.e., r_n=1, all x^{nij}_{km} and y^{nij}_{km} become binary variables. Finally, the vectors $x=\{x^{nij}_{km}\}$ and $y=\{x^{nij}_{km}\}$ are used to denote the primary and backup path routes for a request.

Now the conditional failure probability of a primary path x given stressor $r\epsilon R$, $F^n_r(p^r,x)$, is computed as a product of link failure probabilities, Eq. 1a (and similarly $F^n_r(p^r,y)$ for the backup path y, Eq. 1b). Since routes x and y are link-disjoint, their conditional path-pair failure probability is also given by the product term in Eq. 2. Leveraging the above, the first optimization stage computes skeleton primary/backup path-pairs over $H(U,E)$ using the multi-objective function in Eq. 3. Namely, this function comprises of three weighted components to maximize throughput (F_1), minimize resource usage (F_2), and minimize joint failure probability/risk (F_3), i.e., ω_1, ω_2, and ω_3 are arbitrary weighting factors. Furthermore, additional equations are also introduced to bound the solution, i.e., Eqs. 4 and 5 for flow continuity, Eq. 6 for link-disjointness, Eq. 7 for link capacity bounds, and Eqs. 8-10 for binary conditions.

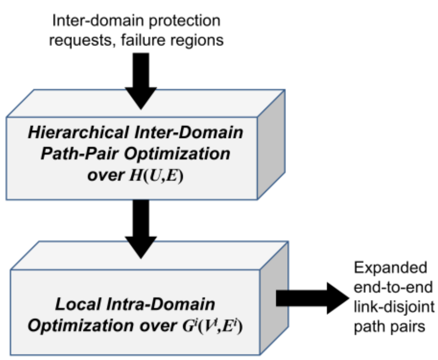

Figure 1: Two-stage optimization approach

$$F_r^n(p^r,x)=1-\prod_{e^{ij}_{km}\in E}(1-p^r_{i_kj_m}x^{nij}_{km}),\ F_r^n(p^r,y)=1-\prod_{e^{ij}_{km}\in E}(1-p^r_{i_kj_m}y^{nij}_{km}) \qquad (1.a,b)$$

$$F_r^n(p^r,x)F_r^n(p^r,y)=(1-\prod_{e^{ij}_{km}\in E}(1-p^r_{i_kj_m}x^{nij}_{km}))(1-\prod_{e^{ij}_{km}\in E}(1-p^r_{i_kj_m}y^{nij}_{km})) \qquad (2)$$

$$\begin{aligned}\text{Min } F &= w_1\sum_{n\in N}(1-f_n)+w_2\sum_{n\in N}\sum_{e^{ij}_{km}\in E}(x^{nij}_{km}+y^{nij}_{km})+w_3\sum_{n\in N}\sum_{r\in R}\pi_r F_r^n(p^r,x)F_r^n(p^r,y)\\ &= w_1F_1+w_2F_2+w_3F_3\end{aligned} \qquad (3)$$

$$\sum_{(j,m):e^{ij}_{km}\in E}x^{nij}_{km}-\sum_{(j,m):e^{ji}_{mk}\in E}x^{nji}_{mk}=\begin{cases}f_n; & if\ v^i_k=s_n\\ -f_n; & if\ v^i_k=d_n\\ 0; & otherwise\end{cases};n\in N \qquad (4)$$

$$\sum_{(j,m):e^{ij}_{km}\in E}y^{nij}_{km}-\sum_{(j,m):e^{ji}_{mk}\in E}y^{nji}_{mk}=\begin{cases}f_n; & if\ v^i_k=s_n\\ -f_n; & if\ v^i_k=d_n\\ 0; & otherwise\end{cases};n\in N \qquad (5)$$

$$x^{nij}_{km}+y^{nij}_{km}\le f_n;n\in N,e^{ij}_{km}\in E \qquad (6)$$

$$\sum_{n\in N}(x^{nij}_{km}+y^{nij}_{km})\le C_2;n\in N,e^{ij}_{km}\in E \qquad (7)$$

$$x^{nij}_{km}\in\{0,1\};n\in N,e^{ij}_{km}\in E \qquad (8)$$

$$y^{nij}_{km}\in\{0,1\};n\in N,e^{ij}_{km}\in E \qquad (9)$$

$$f_n\in\{0,1\};n\in N,e^{ij}_{km}\in E \qquad (10)$$

Figure 2: Multi-objective integer non-linear programming (INLP) model

Skeleton paths generated in the first optimization stage specify all traversed domains. These results drive the second optimization stage to expand the local intra-domain sub-path routes, i.e., “all-optical” segments. The same multi-objective function in Eq. 3 is re-used here at the local domain, i.e., by defining optimizations for $\boldsymbol{G}^i(\boldsymbol{V}^i,\boldsymbol{L}^i)$. After local sub-path optimization is complete, *most-used* (MU) wavelength selection is used to select wavelength channel colors, i.e., as it known to give lower blocking [7]. Finally, combining intra-domain segments (with the same request index) with their respective inter-domain links in $\boldsymbol{H}(\boldsymbol{U},\boldsymbol{E})$ gives the completed end-to-end lightpaths pairs.

However, most INLP problems pose high computational complexity and are difficult to solve for generalized network scenarios. Hence a reduced *integer linear programming* (ILP) approximation is also developed here. Namely, the joint (conditional) failure probability expression in Eq. 2 is expanded and all its higher-order product terms (with three or more probabilities) are removed, i.e., assuming low conditional failure probabilities, p^r_{ikjm}. This results in a modified/simplified expression for the (aggregate) joint risk function, F_3, as follows:

$$\text{Min } F=w_1\sum_{n\in\boldsymbol{N}}(1-f_n)+w_2\sum_{n\in\boldsymbol{N}}\sum_{e^{ij}_{km}\in\boldsymbol{E}}(x^{nij}_{km}+y^{nij}_{km})+\sum_{n\in\boldsymbol{N}}\sum_{r\in\boldsymbol{R}}\sum_{e^{ij}_{km}\in\boldsymbol{E}}\sum_{e^{uv}_{pq}\in\boldsymbol{E}}\pi_r p^r_{i_kj_m}p^r_{u_pv_q}z^{ni_kj_m}_{u_pv_q} \qquad (11)$$

where z^{nij}_{km} is a new binary variable introduced to replace the product of two binary variables $x^{nij}_{km}y^{nij}_{km}$. Overall, the above ILP formulation is much more scalable and also more amenable to existing LP solver packages.

III. Performance Evaluation

The optimization solution is analyzed using a 6-domain network with 25 inter-domain links and 4 equiprobable p-SRLG failure regions, Fig. 3. Inter-domain links have double the wavelength counts of intra-domain links (C_1=8/C_2=16, C_1=16/C_2=32 channels), and the ILP approximation is solved using a combination of the *PuLP* modeler and the *GPLK* solver. The respective objective function weights in Eq. 3 are also set to ω_1=6, ω_2=0.0001, and ω_3=1, i.e., to emphasize throughput maximization. Furthermore, all tests are done for mid-range link failure probability values, i.e., p^r_{ikjm}=0.5. Performance is also compared to the heuristic multi-failure recovery scheme in [6], which jointly computes link-disjoint path-pairs to lower failure probability and TE cost. These tests are done using *OPNET Modeler®* simulation, and requests are processed in random sequential order (infinite holding times).

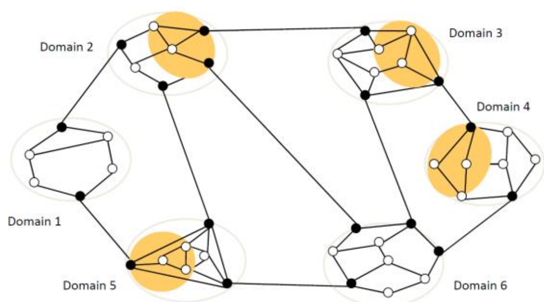

Figure 3: 6-domain test network w. 4 stressor regions (p-SRLG)

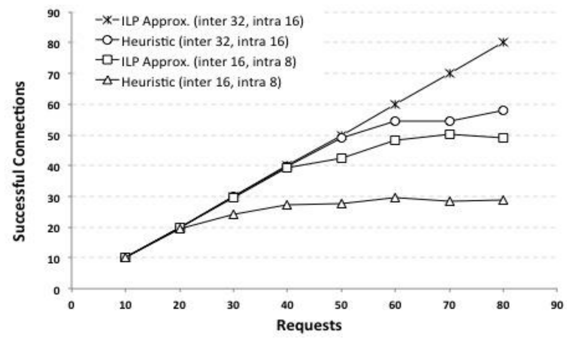

Figure 4: Successful requests (C_1,C_2=8 and C_1,C_2=16)

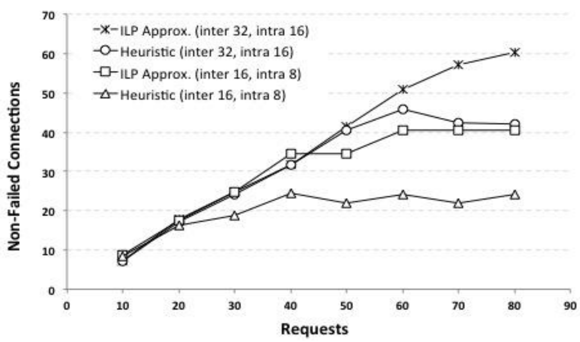

Figure 5: Non-failed requests (C_2=2C_1=16 and C_2=2C_1=32)

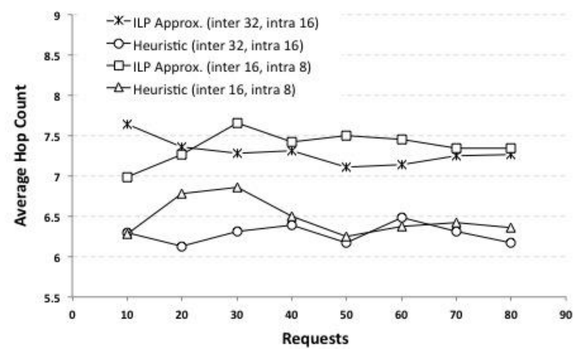

Figure 6: Average hop count (C_2=2C_1=16 and C_2=2C_1=32)

The number of successful setups is first plotted in Fig. 4 for differing random batch sizes. At lower loads, both the heuristic and optimization schemes give very competitive results, as resource contention is low. However, for medium-high load regimes, the optimization scheme does significantly better, yielding almost 50% more setups. The number of *non-failed* demands (i.e., unaffected primary and/or backup routes) is also plotted in Fig. 5. Again, the ILP solution gives much better survivability, especially under more challenging heavy load conditions, e.g., almost 35% less failures for increase link sizes. Finally, the average primary/backup hop counts are also shown in Fig. 6 and indicate slightly higher values with the optimization strategy, i.e., 10-25% (note that similar findings are also observed for single-failure protection optimization [7]). In addition, the ILP results also show a slight decline in resource usage at higher loads. Note that the above tests are also re-run for lower/higher link failure probabilities, i.e., p^r_{ikjm}=0.2 and 0.8, and findings re-confirm optimization gains in term of lower blocking and non-failed requests.

This paper presents a novel optimization scheme to protect multi-domain lightpath connections under probabilistic multi-failure conditions. This necessitates a non-linear formulation, which is then solved using a linear approximation approach to provide notably-improved bounds on blocking and failure recovery rates.

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