Survivable Routing in Multi-domain Optical Networks with Geographically Correlated Failures

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***Abstract*—We address the problem of survivable path pair routing in multi-domain optical networks with geographically correlated failures. The objective is to minimize the risk of simultaneous failure of both the primary and backup paths. We develop a probabilistic model to calculate the simultaneous failure probability of both the paths and consider a topology aggregation scheme for domains based on calculating the physical vulnerable overlapping area of two paths within a domain. We develop an inter-domain minimum overlapping area routing algorithm based on the aggregated information from each domain. We compare our algorithm to Suurballe's Algorithm and an optimal approach and we show that our heuristic approach is effective in reducing the total probability of simultaneous failure.**

***Index Terms*—Multi-domain Optical Network, Survivability, Geographically Correlated Failures, Topology Aggregation.**

I. Introduction

Optical networks may be prone to geographically correlated failures, which not only affect components at the epicenter of the failure, but which may also lead to the failure of neighboring network components, resulting in a tremendous amount of information loss. For example, an earthquake in Nepal in 2015 knocked out thousands of network components due to technical failure. Other examples of events that lead to geographically correlated failures are manmade disasters, such as EMP (electromagnetic pulse) attacks and nuclear attacks [1]. Considering such geographically correlated failures, it is important to protect the ability of the network to continue carrying traffic when such failures occur by developing appropriate survivability mechanisms.

A common approach to providing survivability is to provision protection resources in the network [2]. In path protection schemes, for each working path, a link-disjoint backup path is provisioned in order to protect against the failure of any link along the working path. However, under correlated failures, such an approach may not be effective if links on the primary path share correlated risks with links on the backup path. One approach to deal with correlated failures is through the concept of shared risk link groups (SRLGs), in which each SRLG identifies a set of links that fail simultaneously due to the same risk. In this case, survivability can be provided by provisioning an SRLG-disjoint backup path for each working path. However, the problem of finding SRLG-disjoint paths has been shown to be NP-complete [3]. Furthermore, for the case of geographically correlated failures in which the location of the epicenter of the failure is not known in advance, it may be difficult and impractical to model all possible failure events using SRLGs.

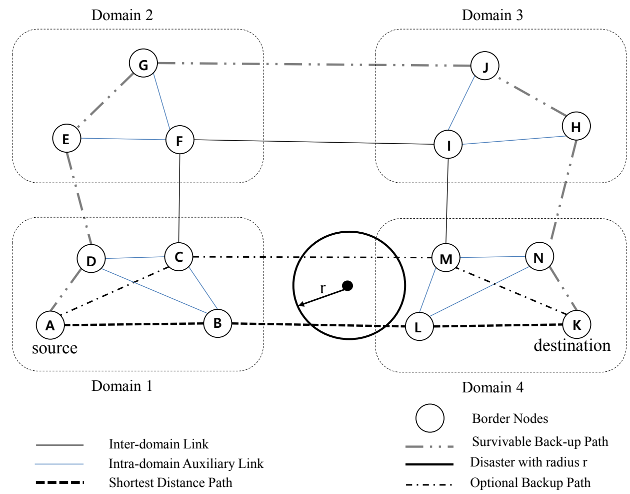

Fig. 1. Survivable routing scheme against a random disk shaped geographically correlated failure with radius r.

The problem of survivability of networks against geographically correlated failures has been extensively studied [1], [4], [5]. The work in [1] includes the use of computational geometric tools to construct algorithms that identify vulnerable points within the network under various metrics. In [4], the authors consider disasters that take the form of random line cuts and emphasize geometric techniques to evaluate average two-terminal reliability towards the study of network resiliency. In [5] the authors study disasters as randomly located disks in the network plane, and using results from geometric probability, they approximate some network performance metrics to such a disaster in polynomial time. Although these papers discuss the impacts of geographical failures, they consider networks as single domain architectures.

Providing survivability in a multi-domain environment is an even greater challenge than in single-domain environments because full information regarding the resources in each domain is often not available due to the privacy policies of domain administrators [6]–[9]. One technique for facilitating path provisioning over multi-domain optical networks is topology aggregation, which is used for exchanging limited domain information while maintaining privacy of domain administrators [10]. In topology aggregation, each domain is represented by an aggregated logical topology in which aggregated links interconnect the border nodes of the domain. The underlying intra-domain paths for the aggregated links are not revealed to other domains. The aggregated topology may also provide some limited information for each of the aggregated links, and the amount of information to be exchanged could depend upon domain policies. In some cases, only the distance of the shortest paths between border nodes is presented in topology aggregation, while some other aggregations might provide information on the disjointness of aggregated links through SRLGs [7].

Survivability in multi-domain optical networks has been a well-researched area. In [9], the authors survey survivability techniques in multi-domain optical networks and compare the performances of different approaches based on different metrics. Most of these works focus on either a single component failure or a small number of simultaneous fiber cuts. Correlated failures of nodes and links are often addressed by shared risk node groups or SRLGs [11]. In [7], Gao et al. propose SRLG-aware topology aggregation approaches that can help to find a pair of inter-domain paths with a minimum set of common SRLGs for multi domain optical networks. In [12], the authors present a protection scheme for multi-domain optical networks for correlated and probabilistic failures using a p-SRLG framework for multi-domain networks. The additional challenge in providing survivability in multi-domain networks with geographically correlated failures is to develop a topology aggregation which provides necessary information about the topological locations of nodes and edges within a domain.

In this paper, we consider the problem of finding a pair of paths (primary and backup) in a multi-domain optical network, such that the probability of simultaneous failure of both the primary path and backup path is minimized. We consider a geographically correlated failure model in which a failure is represented by a circular disk in the plane of the network. It is assumed that all components within the area of this circular disk fail simultaneously. Fig. 1 shows a scenario in which three routing paths from source A to destination K are considered. A circle with radius r shows the network components that are affected by a geographically correlated failure. In this example, if our primary path is $A-B-L-K$ (considering shortest distance path from source to destination) fails, then path $A-C-M-K$ cannot be used as a backup path, since it lies in the same disaster region as the primary path. On the other hand, path $A-D-E-G-J-H-N-K$ is far enough from the primary path that it is less likely to fail at the same time.

To address this problem, we propose a topology aggregation scheme for each domain that provides necessary information about the geographic distances between links in the domain. Then, using this aggregated topology information, we develop a heuristic algorithm to provision primary and backup paths in such a way that they are less likely to fail simultaneously due to a geographically correlated failure.

The rest of the paper is structured as follows. Section II presents the problem statement, description of the network model and failure model, and a probabilistic model to calculate the simultaneous failure probability for two paths. Section III presents details of the topology aggregation scheme, and discusses the algorithm for finding a pair of survivable multi-domain paths based on the topology aggregations. In Section IV, we present the numerical evaluation of our algorithm, comparing it to Suurballe's algorithm and an optimal approach for calculating region disjoint paths. We conclude our paper in Section V.

II. Problem Statement and Failure Modeling

We begin this section by describing our multi-domain network model, followed by the failure model, and then we introduce the concept of vulnerable zone of edges and paths. We also discuss a probabilistic model to calculate simultaneous failure probability for two paths, given that the failure location is uniformly distributed in the plane of the network.

A physical multi-domain network is denoted by a graph G_p (D_p, L_p, C_p), where D_p is a set of domains, L_p is a set of bi-directional inter-domain links and C_p: $L_p \rightarrow \mathbb{R}_+$ is a set of inter-domain link distances. Domain $i \in D_p$ is denoted by graph G_i (V_i, E_i, B_i, C_i'), where V_i is a set of intra-domain nodes for Domain i, E_i is a set of bi-directional intra-domain links for Domain i, B_i is a set of border nodes for Domain i, and C_i': $E_i \rightarrow \mathbb{R}_+$ is a set of intra-domain link distances within Domain i. We assume that inter-domain link distances are greater than intra-domain link distances. We are also given a set of physical coordinates, (X_v, Y_v), that denotes the location of each node $v \in V_i$ in the physical plane of the network. We assume all edge locations are straight lines between nodes in the physical plane of the network.

We model a geographically correlated failure as a circular region of radius r centered at a random location in the physical plane of the network. We assume that there is only one geographically correlated failure in the network at a time, and that all network components located within the area of the circular region of radius r will fail at the same time. The location of the epicenter of the failure is determined by a two-dimensional probability density function $f(x, y)$ defined over the plane of the network.

Based on the failure model, we define the *vulnerable zone of an edge*, $VZ_{e_{(i,j)}}$, as the region around edge $e_{(i,j)}$ in the network plane, such that if the epicenter of a failure is located within this region, it will cause failure of edge $e_{(i,j)}$ [1]. Fig. 2 illustrates the concept of vulnerable zone around an edge. All points within $VZ_{e_{(i,j)}}$ are at a distance of less than r from edge $e_{(i,j)}$. The failure probability ($P_{f_{e(i,j)}}$) of an edge $e_{(i,j)}$ is determined by the probability that a failure occurs in the vulnerable zone of the edge.

The probability that the failure occurs in the vulnerable zone is determined by integrating the failure location probability density function $f(x, y)$ over the vulnerable zone. In the case of uniform distribution of the failure's epicenter location, the probability is directly proportional to the area of the vulnerable zone itself. In general, failure probability ($P_{f_{e(i,j)}}$) of edge $e_{(i,j)}$ can be written as:

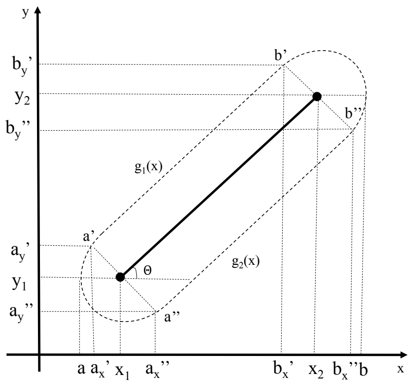

Fig. 2. Geometrical representation for vulnerable zones around an edge.

$$P_{f_{e(i,j)}} = \int_a^b \int_{g_2(x)}^{g_1(x)} f(x,y)\,dx\,dy, \tag{1}$$

where a and b are the leftmost and rightmost points of the vulnerable zone in the x-y plane, and $g_{1(x)}$ and $g_{2(x)}$ are the curves denoting the upper and lower boundaries of the vulnerable zone (see Fig. 2). For the case in which $f(x,y)$ is uniform, $P_{f_{e(1,2)}} = a_{12}/\Omega$, where a_{12} is the area of the vulnerable zone, and Ω is the area of the entire plane of the network. We define the vulnerable zone $VZ_{R(s,d)}$ of a path $R_{(s,d)}$ from source node s to destination node d to be the union of vulnerable zones $VZ_{e_{(i,j)}}$ of all the edges $e_{(i,j)}$ in path $R_{(s,d)}$.

$$VZ_{R_{(s,d)}} = \bigcup_{e_{(i,j)} \in R_{(s,d)}} VZ_{e_{(i,j)}}, \tag{2}$$

$$P_{fR_{(s,d)}} = \int_{VZ_{R_{(s,d)}}} f(x,y)\,dx\,dy, \tag{3}$$

where $P_{fR_{(s,d)}}$ is the probability of failure of path $R_{(s,d)}$. Let $A(R_{(s,d)}, R_{(s',d')})$ be the overlapping region between a path $R_{(s,d)}$ and a path $R_{(s',d')}$:

$$A\left(R_{(s,d)}, R_{(s',d')}\right) = VZ_{R_{(s,d)}} \cap VZ_{R_{(s',d')}}. \tag{4}$$

The probability of $R_{(s,d)}$ and $R_{(s',d')}$ failing simultaneously is then given by:

$$P_A = \int_{A(R_{(s,d)}, R_{(s',d')})} f(x,y)\,dx\,dy. \tag{5}$$

For the case in which the failure location is uniformly distributed, the probability of simultaneous failure is proportional to the area of the overlapping region of the two paths, which is denoted as $\delta(R_{(s,d)}, R_{(s',d')})$. One approach to calculate the area of the overlapping region, $\delta(R_{(s,d)}, R_{(s',d')})$, of two paths, is to overlay an $N \times N$ grid over the plane of the network for a large value of N. Then consider $K = N^2$ grid points at the intersection of the grid lines, and for each of these grid points, if the distance between the grid point and the path $R_{(s,d)}$ is less than r, then the grid point lies in the vulnerable zone $VZ_{R_{(s,d)}}$. Let K' be the number of grid points that fall within the vulnerable zone of both path $R_{(s,d)}$ and $R_{(s',d')}$.

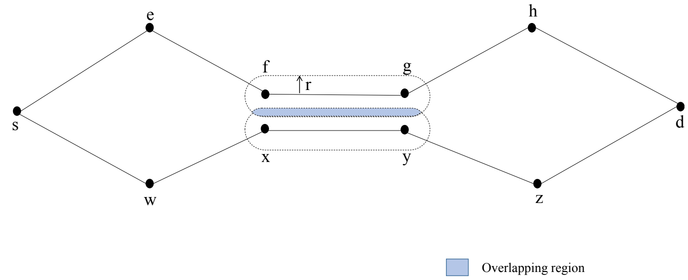

Fig. 3. Representation of the overlapping region of two paths between a pair of border nodes.

The *area of the overlapping region* of the two paths (refer Fig. 3) can then be estimated as (K'/K) multiplied by the area of the entire plane of the network, Ω.

$$\delta\left(R_{(s,d)}, R_{(s',d')}\right) = (K'/K) \times \Omega. \tag{6}$$

The area of the overlapping region, $\delta(R_{(s,d)}, R_{(s',d')})$, is used in the topology aggregation scheme to assist in finding pairs of paths through a domain that have minimum overlapping areas, which indicates that the paths are less susceptible to a common geographically correlated failure.

Given the above framework, the goal is to develop a topology aggregation scheme that takes into account the area of the overlapping region of two paths, and to use the information provided by the topology aggregation scheme to find two multi-domain paths from s to d such that the area of the overlapping region of the two paths is minimized.

III. Heuristic Algorithm

In this section, a heuristic algorithm i.e. Minimum Overlap Area Routing Algorithm *(MOA)* is proposed, to provision primary and backup paths using the topology aggregation information provided by each domain.

A. Topology Aggregation

Due to the privacy restrictions on the exchange of complete domain information with other domains in the network, topology aggregation may be used to exchange limited information about each domain. Typically, topology aggregation provides an aggregated logical topology for each domain, along with some information on the properties of the links in the topology. Common logical topologies used in topology aggregation schemes include: single node, star, and full mesh topologies [10]. In our work, we consider full mesh network topology aggregation, in which border nodes within a domain are connected in full mesh pattern using aggregated links. All the aggregated links between the border nodes are mapped to physical paths in the substrate network. For each aggregated link, the topology aggregation scheme will also provide the distance of the underlying path in the substrate network, but will not provide detailed routing information of the underlying path. We propose to extend the information provided in the topology aggregation to also include information that will assist in finding pairs of paths through a domain that have minimum-area overlapping regions.

In this work, we consider two separate full-mesh topology aggregations for each domain. The first topology aggregation, called the *primary topology aggregation*, maps each aggregated link between two border nodes to the minimum distance path between those border nodes. The total distance of the path is associated with the corresponding aggregated link in the topology aggregation. The primary topology aggregation is used to find a minimum-distance primary path in the inter-domain topology.

If an aggregated link in the primary aggregated topology is selected for the primary path, we create a *secondary aggregated topology*. In this secondary topology (also a full-mesh topology), each aggregated link is mapped to a path in the domain that has a combination of minimum distance and minimum overlapping area with the path used for the primary path's aggregated link. The approach for calculating a minimum-overlap path is as follows:

Step 1: Let P' represent a set of physical links used in the physical path of the aggregated link selected for the primary path in the domain m and let P represent a set of physical links in the domain m, that are not in set P'.

Step 2: Calculate the area of the overlapping region of each physical link $e_{(i,j)} \in P$ with the physical links in the primary path, P'.

Step 3: Set the weight of each physical link $e_{(i,j)} \in P$ to $W_{e_{(i,j)}}$, considering both the area of the overlapping region and the distance:

$$W_{e_{(i,j)}} = \alpha \times \delta \left(e_{(i,j)}, \hat{e}_{(i',j')} \right) + (1 - \alpha) \times \text{dis} \left(e_{(i,j)} \right), \quad (7)$$

where α is a tradeoff parameter between the overlap area and distance. $\text{dis}(e_{(i,j)})$ is the distance of physical link $e_{(i,j)}$, and $\delta(e_{(i,j)}, \hat{e}_{(i',j')})$ is the area of the overlapping region between physical link $e_{(i,j)}$ and the physical path for the aggregated link $\hat{e}_{(i',j')}$ used in the primary path. Varying the value of parameter α, allows us to achieve a trade-off between the distance of the backup path and the area of the overlapping region of the backup path with the primary path. For lower values of α, shorter distance paths are selected, and for higher values of α, paths with less overlapping area are selected.

Step 4: Calculate the minimum distance paths between each pair of border nodes in the domain m using the new metric $W_{e_{(i,j)}}$.

The aggregated topology information provided with the secondary aggregated topology includes the distance of the associated paths for each aggregated link and the area of the overlapping region between the path for each aggregated link and the path for the aggregated link used for the primary path, as in Equation 6. Note that, if a domain is not used by the primary path, then its secondary topology aggregation is the same as its primary topology aggregation, and the area of the overlapping region is zero.

An example is shown in Fig. 4, which explains the concept of primary topology aggregation and secondary topology aggregation between a pair of border nodes for a given domain. Suppose a and d are two border nodes within a domain. For simplicity, let us assume the weights of the links to be

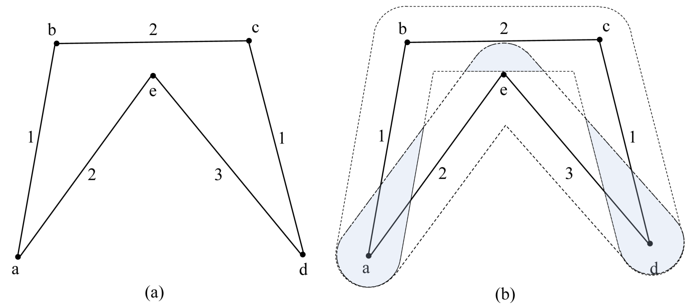

Fig. 4. (a) Primary topology aggregation which is created by selecting the minimum distance path between border nodes within a domain. (b) Secondary topology aggregation which considers the combination of minimum distance and sum of overlapping regions between border nodes within a domain.

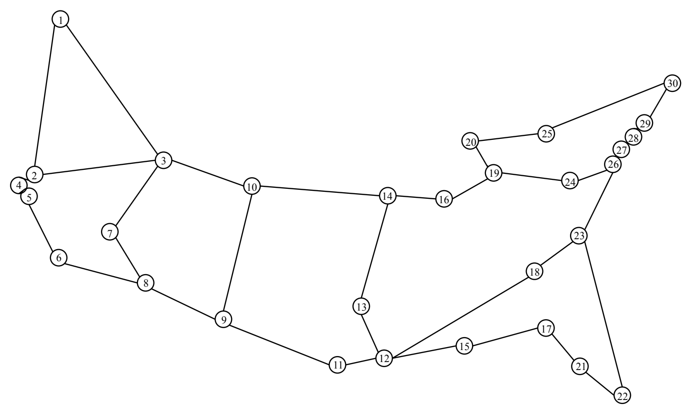

Fig. 5. A 30 node US topology for inter-domain connections.

the distances between them. To create the primary topology aggregation, we find the minimum distance path between the border nodes a and d, i.e. path $a - b - c - d$. Now, the aggregated link weight is the distance of the shortest path between the border nodes a and d which is 4. Now, suppose that the aggregated link $\hat{e}_{(a,d)}$ is selected for the primary path in the over-all inter-domain topology. We construct a secondary topology aggregation of this domain by considering paths that minimize a combination of distance and area of the overlapping region with the path used for aggregated link $\hat{e}_{(a,d)}$ in the primary topology aggregation. The aggregated link weight after the secondary aggregated topology is a linear combination of the path distance and the overlapping area with the primary path.

B. Path Selection

Once the topology aggregation is provided, we consider the problem of finding two inter-domain paths over the inter-domain topology. To calculate the primary path between a source node and a destination node in the inter-domain network, we construct an inter-domain topology consisting of the primary aggregated topologies of each domain, with the weight of the aggregated links set as the distance of the underlying paths. We then find the minimum distance path in the inter-domain topology and set this as the primary path.

For the backup path calculation, we determine the secondary aggregated topologies of each domain based on the aggregated

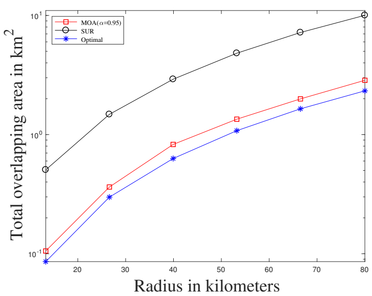

Fig. 6. Overlapping area of primary and backup path (proportional to the probability of simultaneous failure P_A as in Eq. 5) versus the radius of failure in kms.

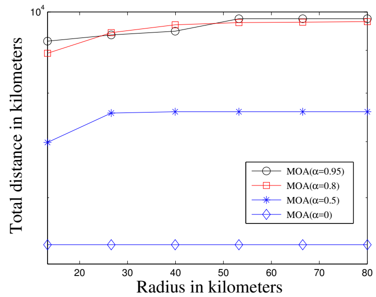

Fig. 8. Total distance versus radius of failure in kms for different values of α.

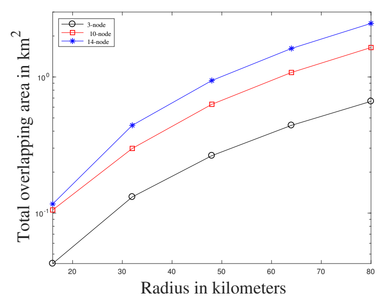

Fig. 10. Overlapping area of primary and backup path versus radius of failure in kms for 3 different intra-domain topologies at $\alpha = 0.95$.

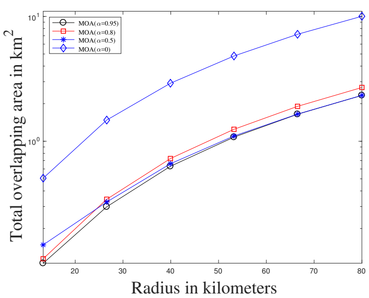

Fig. 7. Overlapping area versus radius of failure in kms for different values of α.

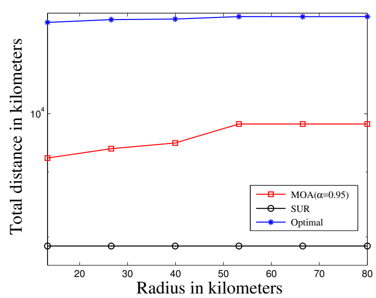

Fig. 9. Total distance of primary path and backup path versus the radius of failure in kilometers for $\alpha = 0.95$.

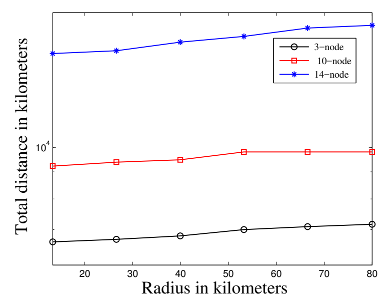

Fig. 11. Total distance versus radius of failure for 3 different intra-domain topologies at $\alpha = 0.95$.

links selected by the primary path in each domain. An inter-domain topology is constructed by combining these secondary aggregated topologies, and the weight of the aggregated links are set to $\widehat{W}_{\hat{e}_{(i,j)}}$. We denote it by:

$$\widehat{W}_{\hat{e}_{(i,j)}} = \beta \times \delta\left(\hat{e}_{(i,j)}, \hat{e}_{(i',j')}\right) + (1-\beta) \times \text{dis}\left(\hat{e}_{(i,j)}\right), \quad (8)$$

where β is the tradeoff parameter between overlap area and distance, similar to α. $\delta(\hat{e}_{(i,j)}, \hat{e}_{(i',j')})$ is the area of the overlapping region between the physical path for aggregated link $\hat{e}_{(i,j)}$ and the physical path for the aggregated link used for the primary path $\hat{e}_{(i',j')}$. dis$(\hat{e}_{(i,j)})$ is the distance of the physical path for the aggregated link $\hat{e}_{(i,j)}$. We then find our backup path based on this new inter-domain topology by calculating minimum distance paths based on $\widehat{W}_{\hat{e}_{(i,j)}}$ for all aggregated links. We assume that the connection fails if either source or destination is in the disaster area.

IV. Numerical Evaluation

A. Network Settings

For numerical evaluation of our approach, we consider a modified version (i.e. nodes are replaced by domains) of a 30 node US topology (Fig. 5) for inter-domain connections [13]. We then consider randomly-generated 10 node topologies for the intra-domain topologies (with a degree of 2-4 for each node). We assume that the area of each domain is $80 \times 80\ km^2$, so that no domains in the network overlap. (X, Y) coordinates of the 30 inter-domain nodes indicate the location of the center of the domains. Intra-domain coordinates are generated randomly within a network plane within a given distance of the center of the domain. Intra-domain link distances ranges from 50 to 70 kilometers and inter-domain link distances are determined by the coordinates in the 30 node topology, which are much higher than intra-domain link distances. We generate 1000 random source and destination (s, d) pairs over a fixed network topology, to include (s, d) pairs with different distance between them. Primary and backup paths are calculated using the aggregated topologies. We ignore the connection if no backup path exists for some (s, d) pair. We assume parameter $\alpha = \beta$ for Fig. 6 to Fig. 11. Simulations were also run for cases in which $\alpha \neq \beta$, and similar trends were observed.

B. Experiments and Discussions

We compare the Minimum Overlap Area Routing Algorithm, denoted by *MOA* in Fig. 6, with Suurballe's Algorithm *SUR* [14], which is used to compute two link disjoint paths between source s and destination d over the aggregated topologies using only distance information. We also compare the *MOA* algorithm to an optimal solution in which we assume complete domain information is exchanged with other domains, and there is no construction of aggregated topologies. The optimal algorithm will select a minimum-distance primary path and will select a backup path with minimum overlapping area from the primary path. In this experiment, α is set to 0.95. Fig. 6 shows that the overlapping area of primary path and backup path increases with an increase in the radius of failure. As the radius increases, the $VZ_{e_{(i,j)}}$ around each edge increases, and thus, finding a completely non-overlapping path becomes difficult. Our results also show that the *MOA* algorithm outperforms the *SUR* algorithm with respect to minimizing the overlapping area and is very comparable to the optimal solution. As from Eq. 5, the total overlapping area of the primary and backup path is proportional to the probability of both paths failing simultaneously, therefore we can conclude from this experiment that P_A of the *MOA* algorithm (which uses topology aggregation) is comparable to the optimal solution, that relies on full disclosure of intra-domain topology information.

In Fig. 7, we compare the overlapping area values of primary and backup paths for different α values for the *MOA* algorithm. As we increase the value of α, the overlapping area for primary and backup paths decreases. For $\alpha = 0$, the weights of the aggregated links are based only on the distance, and thus, the total overlapping area is greater. In Fig. 8, we compare the total distance (i.e. total distance of primary and backup path) for different values of α. For the *MOA* algorithm, the distance increases gradually with increase in radius because an increase in radius leads to an increase in $VZ_{e_{(i,j)}}$ for each link. For the high values of α, the algorithm gives more preference to disjointness of area rather than minimizing distance, to provide a more survivable pair of paths. Thus, to minimize the total overlapping area, the backup path may traverse a greater number of inter-domain links, resulting in an increase in distance. For the low values of α, the algorithm gives more preference to distance effectiveness rather than disjointness. When $\alpha = 0$, the total distance does not change with radius because the *MOA* algorithm will only calculate the backup path considering the distance, without considering the overlapping area of the two paths.

Next, we compare the three algorithms with respect to the total distance of the resulting paths. In Fig. 9, the total distance for the *SUR* algorithm is constant because it doesn't consider the area of the overlapping region. For the *MOA* algorithm, the distance increases with increase in radius because an increase in radius leads to an increase in $VZ_{e_{(i,j)}}$ for each link. Results of Fig. 9 are recorded at $\alpha = 0.95$. For the optimal algorithm, the distance is the highest because it tries to calculate the most disjoint path from the primary path in the network.

At last, we consider three different intra-domain topologies with 3, 10, and 14 nodes. Intra-domain distances ranges from 50 to 70 kilometers with a degree of 2 to 4 for each node. The inter-domain topology is the same 30 nodes topology [13]. In Fig. 10, we compute the overlapping area between primary and backup paths, for a high value of α = 0.95. We observe that the overlapping area increases as the intra-domain topologies become denser. This happens because in a denser topology, the vulnerable zones around each edge would overlap with the vulnerable zones of other edges, and this increases the total overlapping area of two paths. In Fig. 11, we evaluate the total path distance for the *MOA* algorithm in the three topologies. We observe that the total distance increases with the increase in number of intra-domain nodes for each domain. We also observe gradual increase in the total distance for each topology with the radius, for the same reason as mentioned for Fig. 9.

V. Conclusion

In this paper, we addressed an important aspect of survivability in multi-domain optical networks with geographically correlated failures. We develop a topology aggregation scheme providing information about geographic distances between links in each domain and use this information to provision primary and backup paths, such that these paths are less likely to fail during the same geographically correlated failure event. Numerical evaluations discussed in this paper indicate the effectiveness of our approach in terms of probability of simultaneous failure and total distance.

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