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Maximally Spatial-Disjoint Lightpaths in Optical Networks

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Article Info	ABSTRACT
	Lightpaths enable end-to-end all-optical transmission between network nodes. For survivable routing, traffic is often carried on a primary lightpath, and rerouted to another disjointed backup lightpath in case of the failure of the primary lightpath. Though both lightpaths can be physically disjointed, they can still fail simultaneously if a disaster affects them simultaneously on the physical plane. Hence, we propose a routing algorithm for provisioning a pair of link-disjoint lightpaths between two network nodes such that the minimum spatial distance between them (while disregarding safe regions) is maximized. Through means of simulation, we show that our algorithm can provide higher survivability against spatial-based simultaneous link failures (due to the maximized spatial distance).

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1.   INTRODUCTION

Optical networks provide highly scalable network connectivity, enabling huge aggregated data transfer over very long distances. The occurrences of natural and anthropogenic disasters can have a devastating impact on the topological connectivity of these networks. In 2006, the earthquakes in Taiwan has cut multiple fibers connecting Asia and North America at sixteen different places, reducing the internet capacity of Hong Kong and China by 100% and 74%, respectively [1]. In 2008, the Mediterranean Sea fiber cuts caused the 70% loss of Egypt's connections to the outside world and 50% to 60% loss of India's outbound connectivity on the westbound route [2]. In 2015, an earthquake affected the rural information and communication technology infrastructure and services in Nepal [3, 4], causing a lot of damage in the form of collapsing of houses, schools, access centers, transmission towers, and failures of fiber backhaul and microwave links.

Disjoint lightpaths (pair of primary and backup lightpaths between two network nodes) [5] may consist of spatially-close fibers, which can cause concurrent failure of both lightpaths in the event of a disaster. There are many reasons for which fibers can be spatially-closed. Occasionally, to avoid higher cost of digging ducts, different fibers may have been placed together using a single duct. Figure 1 shows an example of duct sharing as spatially-close overlapping fiber. Fiber endpoints may also be spatially-close due to existing infrastructures or geographical characteristics. Non-overlapping fibers may also be spatially-close due to the close vicinity of their ducts. Although disjointed lightpaths can be physically disjointed, the existence of spatially-close fibers within their fiber sets risks the lightpaths to be affected simultaneously by a disaster occurrence. Hence, increasing the minimum spatial distance of disjoint lightpaths is important for network operators in order for them to ensure the robustness of network services against disaster-based failures.
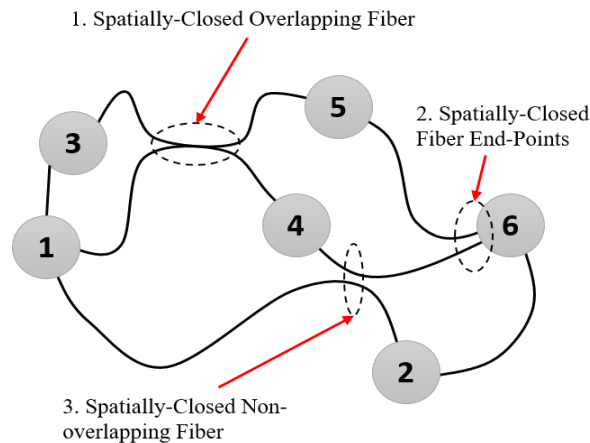
Figure 1. Types of Spatially-close Fibers

Figure 2 shows two link-disjoint paths {1 → 2 → 6} and {1 → 4 → 6}, where fibers 1 → 2 and 4 → 6 are spatially-close. Commonly, fibers are installed in non-straight manner between point-of-presences due to terrains, existing infrastructures and governing rules. We approximate fiber as a concatenation of multiple fiber segments of varying lengths, and can be mapped on geodetic co-ordinates (latitudes and longitudes) or translated into corresponding two-dimensional Cartesian co-ordinates. The remainder of the paper is as follows. Section II presents the related work. Section III provides the problem formulation and our proposed routing algorithm. Simulation results are presented in Section IV. Section V concludes the paper.
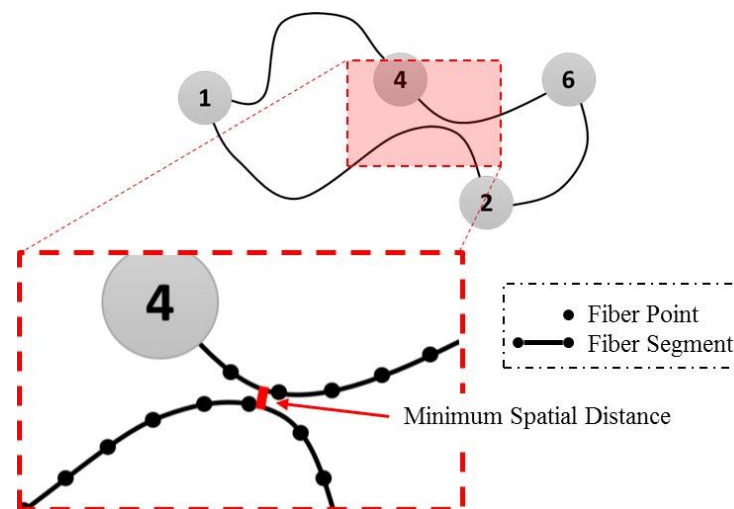

Figure 2. Example of a Pair of Link-disjoint Lightpaths with Minimum Spatial Distance

2.   RELATED WORK

Disasters are inevitable, and can disrupt the network services significantly [6]. During the recent years, a lot of work has been conducted to address the issue of disaster vulnerabilities with different perspectives like natural disasters, electromagnetic pulse, weapons of mass destruction attacks, specific geographical locations and region-aware network augmentation to discourse the influence of a regional failures [7, 8-19]. The impact of failure events on network's services and capacity can be determined from the network geography. Dikbiyik et al. [9], proposed solutions to prevent connection failures from disasters through proactive approaches where damages and cascading failures are estimated as specific events like floods, hurricanes, earthquakes, and occurring in specific geographical locations. In [11], Neumayer et al. presented the geographic-based failure as generalized min-cut and max-flow problems, where a rival tries to

reduce the network connectivity by multiple attacks. They proposed polynomial-time algorithm for the geographic min-cut problem and several approaches for the geographic max-flow problems.

Iqbal et al. [14] considered the geographical information of network nodes and links and include the notion of time-based disaster impact, for finding the risk profile of different network areas at different times. The rationale is that some disasters, like hurricanes, may traverse different network area at different times. They then provided polynomial-time algorithms to assess the most vulnerable network connections. Iqbal et al. [15] also proposed fast running algorithms for detecting spatially-closed fibers and grouping them using the minimum number of distinct risk groups. Agrawal et al. [16], proposed a scheme referred to as the Seismic Zone Aware Node Relocation (SZANR), based on the information on seismic zones by meteorological departments and other similar agencies. Results showed that significant enhancement in the network survivability can be attained in events of earthquakes through promptly minute changes in the network topology.

Sousa et al. [19] addressed a similar problem to this paper, the path geo-diversification problem, where a demand between two network nodes is supported by a pair of geographically-separated paths of a minimum distance. They proposed an ILP to solve the problem. In the same context, Wang et al. [20] presented a geographic aware route selection algorithm for finding alternative paths with appropriate geographical separation, referred to as the proximity factor. Contrary to their work, our proposed algorithm is based on the Yen's algorithm [21], such that the running time and accuracy of our algorithm can be tuned based on the selected K value. ILP are often too time-consuming and our proposed algorithm provide the means for reducing the running time for finding a viable solution to the problem, albeit with lower optimality. However, when k is unbounded, our proposed algorithm will always find the most optimal solution.

3.   PROBLEM FORMULATION AND PROPOSED ALGORITHM

Let an undirected graph $G(N, L)$ represents a physical network, where $N = \{n_1, n_2, n_3, \cdots, n_N\}$ is the set of $|N|$ nodes and $L = \{l_1, l_2, l_3, \cdots, l_M\}$ is the set of $|M|$ undirected links representing bidirectional optical fibers. $P = \{P_1, P_2, P_3, \cdots, P_k\}$ is the set of candidate shortest lightpaths from source node s to destination node t and $w = \{w_1, w_2, w_3, \cdots, w_k\}$ is the set of corresponding path weights. (P_u, P_v) then represents the link-disjoint pair of lightpaths with corresponding path weight pair (w_u, w_v).

1. Provisioning of Disjoint Pair with Maximized Minimum Spatial Distance (DPMMSD) Problem:
2. Find a pair of link-disjoint lightpaths $(\boldsymbol{P_u}, \boldsymbol{P_v})$ between two specific network nodes such that the minimum spatial distance between the lightpaths is maximized.

We proposed the DPMMSD algorithm in the context of the mentioned problem. The algorithm is divided into two parts. The first part of the algorithm finds K number of shortest paths between nodes s and t in the given network (using Yen's algorithm [21]). Other k-shortest path routing algorithms may also be used instead. The second part of the algorithm proceeds from line 3 to line 11. Line 5 confirms whether a pair (P_u, P_v) of shortest lightpaths is link-disjointed. If pair (P_u, P_v) is link-disjointed, then the corresponding minimum spatial distance (msd) and the average minimum spatial distance (msdAvg) of the pair is computed in line 7 using Algorithm 3 (a modified form of the algorithm proposed in [15] to detect spatially-closed fibers, based on the use of k-d tree and k nearest neighbor search [22-24]). In some cases, multiple link-disjoint pairs may have same maximum value of minimum spatial distance. Hence, we introduce another supporting decision variable, the average minimum spatial distance (msdAvg) that represents the quantitative disjointness between the lightpaths, as a tiebreaker. Line 8-11 selected the link-disjoint pair of lightpaths based on msd and msdAvg values with maximized minimum spatial distance.

Algorithm 1: *Provisioning of Disjoint Pair with Maximized Minimum Spatial Distance (DPMMSD)*

Input: An adjacency matrix G of the network, source node s, destination node t, desired number of shortest paths K and geodetic locations data in the form of (x_1, y_1) and (x_2, y_2) for each fiber segment.
Output: A pair of link-disjoint lightpaths with maximized minimum spatial distance.

1:      *mmsd*:=-1, *mmsdAvg*:=-1
2:      Find $\boldsymbol{K}$ shortest lightpaths $P = \{P_1, P_2, P_3, \cdots, P_k\}$ and weights $w = \{w_1, w_2, w_3, \cdots, w_k\}$ from s to t using Yen's algorithm.
3:      **for** u **from** 1 **to** *K-1*
4:          **for** v **from** *u+1* **to** *K*
5:              *matched*:=LinkMatching (P_u, P_v) using Algorithm 2.
6:          **if** *pair* (P_u, P_v) **not** *matched*   i.e. disjointed pair
7:              [*msd*, *msdAvg*] := Computing the minimum spatial distance (*msd*) and average msd of disjoint pair (P_u, P_v) using Algorithm 3.

8:   **if** *mmsd<msd* **and** *mmsdAvg<msdAvg*
9:   *mmsd***:=***msd*
10:   *mmsdAvg***:=***msdAvg*
11:   *ConstrainedPair***:=** (P_u, P_v)

Algorithm 2: *LinkMatching Algorithm*

Input: A pair of lightpaths (P_u, P_v).
Output: If any link of a lightpath P_u matched with any link of lightpath P_v then return *true* else *false*.

1:   matched**:=** false
2:   **for** each fiber links e_{P_u} in lightpath P_u
3:   **for** each fiber links e_{P_v} in lightpath P_v
4:   **if** $e_{P_u} == e_{P_v}$
5:   matched **:=** *true*
6:   return

Algorithm 3: *Computing the Minimum Spatial Distance for a Link- Disjoint Pair using k-d Tree*

Input: A pair of link-disjoint lightpaths $(P_u = \sum_1^i L_{ui}, P_v = \sum_1^j L_{vj})$ such that $l_u \in L_u$ is the fiber segment associated with two fiber points (x_{u1}, y_{u1}) and (x_{u2}, y_{u2}) of known geodetic locations from a fiber link L_u, and $l_v \in L_v$ is the fiber segment associated with two fiber points (x_{v1}, y_{v1}) and (x_{v2}, y_{v2}) of known geodetic locations from a fiber link L_v. Given set L_u and L_v are the fibers joining the intermediary nodes while traversing the paths from start node to destination node.
Output: Minimum spatial distance (*msd*) and average minimum spatial distance (*msdAvg*) between the lightpaths of disjoint pair (P_u, P_v).

1:   Suppose for the lightpaths P_u and P_v, *msd***:=** ∞, *totalPoints***:=** 0, *msdSum***:=** 0, *msdAvg***:=** 0
2:   **for** each fiber L_{vj}
3:   **for** each segment l_v
4:   Compute the segment midpoint m_{l_v}. Insert fiber segment joining points (x_{v1}, y_{v1}), (x_{v2}, y_{v2}) and m_{l_v} into the k-d tree Q
5:   **for** each fiber L_{ui}
6:   **for** each segment l_u
7:   Compute the segment midpoint m_{l_u}.
8:   Find nearest neighbor distance *{d₁, d₂, d₃}* of points (x_{u1}, y_{u1}), (x_{u2}, y_{u2}) and m_{l_u} using kNN search and k-d tree Q, however ignore source and destination nodes.
9:   *d* **:=** *minimum of{d₁, d₂, d₃}*
10:   **if** *msd>d*
11:   *msd***:=***d*
12:   *msdSum***:=***msdSum + d*
13:   *totalPoints***:=***totalPoints + 1*
14:   *msdAvg***:=***msdSum / totalPoints*

For geo-calculations over a great-circle (i.e. finding distance, mid-point, intermediate point etc.) between two latitude and longitude points, we used the formulae given in [25]. We also exclude certain fiber parts (within an exclusion distance from the source and the destination nodes) from the distance computation. Exclusion distance (δ) is the radius of the circular region for which the source node, destination node and enclosed fiber parts are assumed safe. The minimum spatial distance will be measured after this distance. The upper bound time complexity of Yen's Algorithm is $O(KN^3)$ [21] where K is the number of shortest paths and N is the number of nodes. Hence, the worst-case time complexity of our proposed algorithm is $O(K^2 L^2 S_{max}^2)$, where L is the number of total fiber links and S_{max} is the maximum number of fiber segments per fiber.

4.   SIMULATION RESULTS

We simulate the performance of our algorithm using the European network. Performance and efficiency is analyzed while varying different parameters such as shortest paths (K), exclusion distance from source and destination nodes (δ), computing time. The algorithm is coded in MATLAB R2016a and

simulations are performed on 3th Generation Intel® Core i5-3210M 2.5 GHz machine of 6 GB RAM. All simulation results are averaged over 1000 runs.
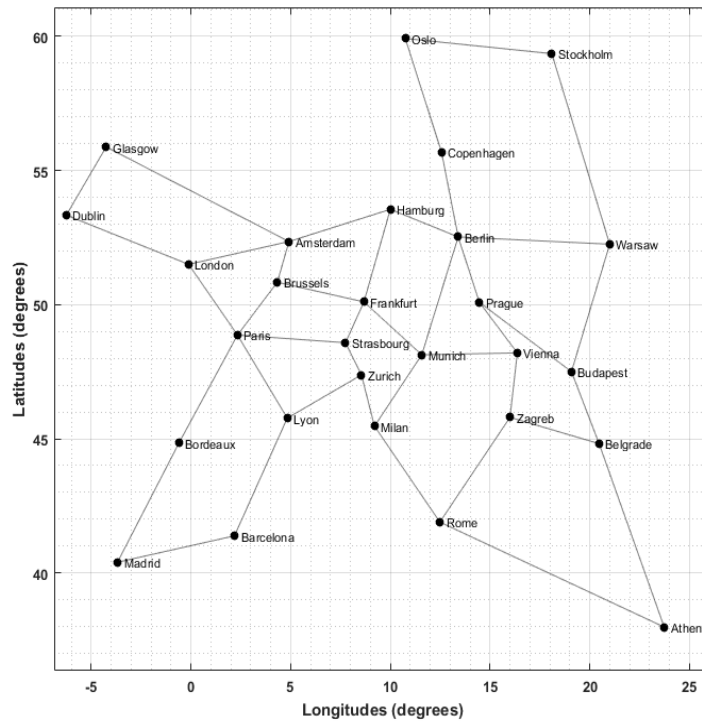

Figure 3: Geographically Mapped European Network

Figure 3 shows a representation of the European network [26], where nodes are mapped as per corresponding geodetic co-ordinates (latitudes and longitudes) in degrees.
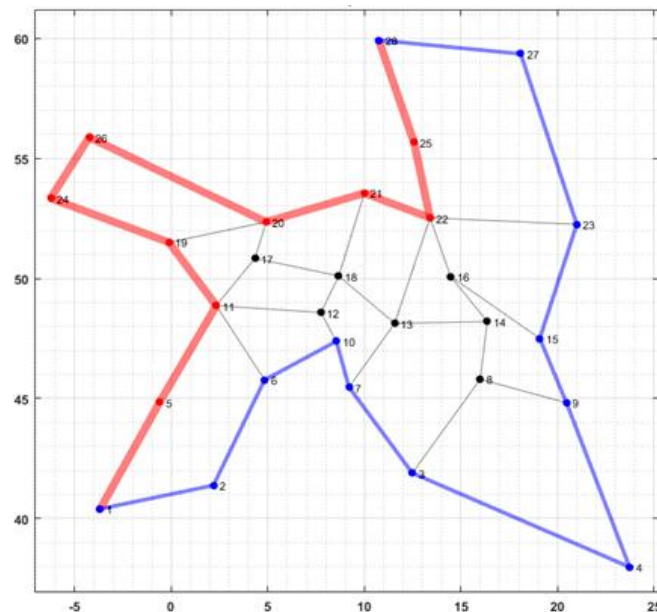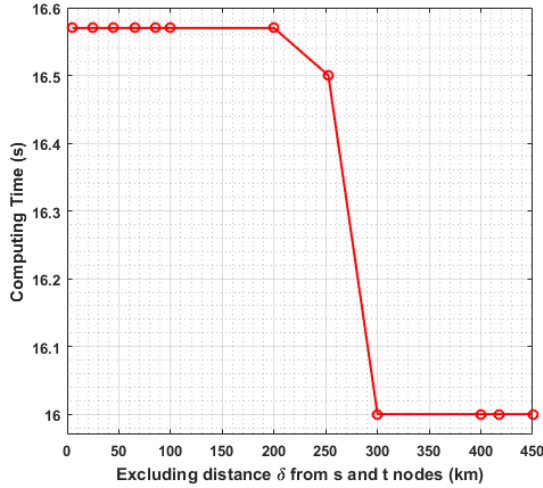

Figure 4: Graph of spatial-disjoint Pair with Minimum Spatial Distance of 223.42 km

Figure 4 shows an example of a spatial-disjoint pair having minimum spatial distance 223.42 km between two lightpaths on the European network. Red and blue colored paths indicate primary path and backup path of the disjoint pair respectively.


(a) Exclusion Distance vs Computing Time
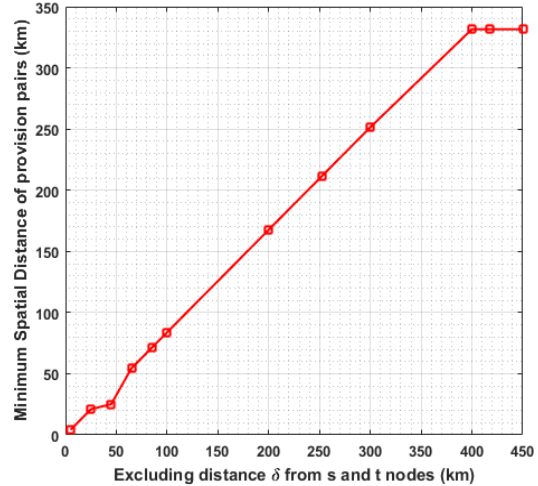
(b) Exclusion Distance VS Minimum Spatial Distance

Figure 5: Effect of Excluding Distance on Computing Time and Minimum Spatial Distance

Figure 5(a) shows the declining impact of δ on the computing times for our proposed algorithm in European network. As we increased δ, more fiber segments are ignored from the measurement of minimum spatial distance, reducing the computation time. Similarly, δ also affects the minimum spatial distance as shown in Figure 5(b). When δ is increased to a certain value, then the minimum spatial distance becomes constant.
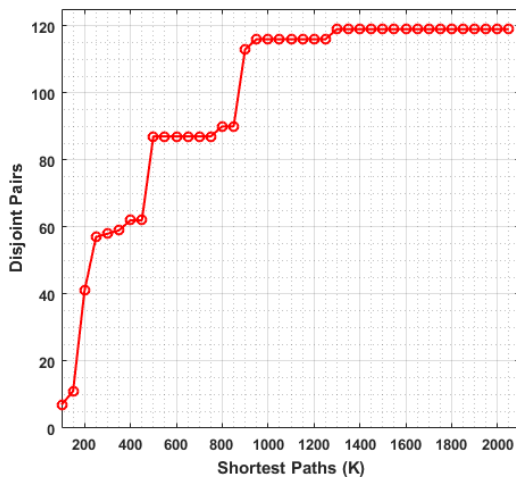
(a) Shortest Paths vs Disjoint Pairs
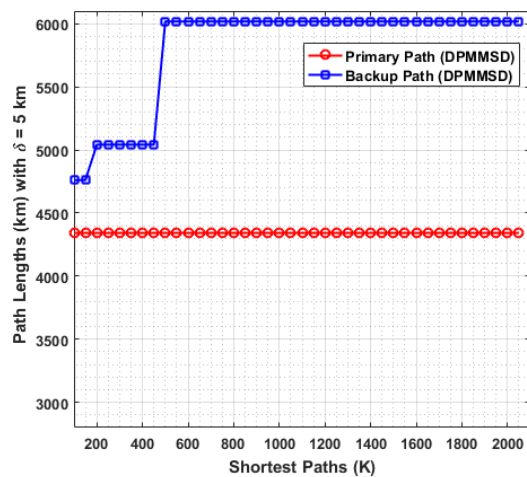
(b) Shortest Paths vs Path Lengths

Figure 6: Effect of K on Computation of Disjoint Pairs and Path lengths when δ = 5 km

The effect of the number shortest paths (*K*) on the computation of disjoint pairs and path lengths for our algorithm is shown in Figure 6(a). The total number of disjoint path pairs depends on the total nodes and fiber links within the network. Figure 6(b) shows the variation of primary and backup path lengths by changing *K* in the algorithm. The path becomes lengthy since DPMMSD provisioned a disjoint lightpath pair without considering path lengths (path lengths are not the main objective of the algorithm, which is maximizing the minimum spatial distance). During simulation, it was observed that most of the running time is consumed at finding and computing disjoint path pairs and their spatial distance. The processing time rises almost linearly when *K* is increased. For the network, the maximum value of obtained *K* is 2037 (119 link-disjoint path pairs). The computation time will be constant when all possible *K* and disjoint pairs have been obtained and no further pair can be found by increasing *K*.

5.   CONCLUSION

In this paper, we have proposed a routing algorithm for provisioning a pair of link-disjoint lightpaths between two network nodes with maximum value of minimum spatial distance. Through simulation, we have shown that our algorithm can increase network survivability against spatial-based concurrent fiber failures, albeit with higher path weights. Maximally spatial-disjoint lightpaths have higher survivability against failing simultaneously in the event of spatial-based disaster occurrences on the physical plane. We have also tested the performance of our algorithm using a real-life optical network topology, where the running time and accuracy of our proposed algorithm can be tuned based on the number of considered shortest paths.

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