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ORIGINAL PAPER

On spatially disjoint lightpaths in optical networks

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Abstract
The core network in the information communication technology infrastructure is based on the optical fiber technology. The core network is of prime importance because it connects all the central offices in the wired communication networks and the mobile switching centers in the wireless communication networks. The optical link between two network nodes is a lightpath, which offers very high speed, low loss, lower cost, highly reliable, secure and very high capacity, end-to-end communication over a very long distance. Any damage to a lightpath in the event of a disaster may lead to massive service interruptions and financial losses for the network operators. Therefore, survivable routing in these networks is very important. Generally, the survivability is ensured by having a backup lightpath to keep communication intact because the primary and the backup light paths are always disjoint. However, they may still fail simultaneously in the event of a large-scale disaster, if their separation distance in the physical plane is small. Hence, the spatial distance between the disjoint lightpaths should also be taken into consideration when establishing the lightpaths. Our contributions in this paper are twofold: (1) a routing algorithm is proposed for provisioning a pair of link-disjoint lightpaths between two network nodes such that their minimum spatial distance (while disregarding safe regions) is maximized, and (2) another routing algorithm is proposed for provisioning a pair of link-disjoint lightpaths such that the path weight of the primary lightpath is minimized, subject to the constraint that the backup lightpath has some particular geographical distance from the primary lightpath. Through extensive simulations, we show that our first algorithm can provide maximum survivability against spatial-based simultaneous link failures (due to the maximized spatial distance), whereas the second algorithm can tune the spatial distance between the lightpaths keeping in view the target survivability requirements and the path weight for the primary lightpath.

Keywords Survivability · Network reliability · Disaster-aware routing · Spatially close fibers · Minimum spatial distance · Optical networks

1 Introduction

Optical networks offer very high capacity, low loss, and reliable communication lightpaths that are used to establish high-speed data communication links over very long distances. Disasters, either natural or fabricated, can be very devastating as they can disrupt the topological connectivity of these networks. Recent disaster scenarios like the earthquake in Taiwan damaged many optical fibers leading to the failure of multiple lightpaths at sixteen different places in North America and Asia. This resulted in severe reduction in the internet capacity of China and Hong Kong by 74 and 100%, respectively [1]. In 2008, the ship anchors in the Mediterranean Sea caused fiber cuts leading to 70% loss of Egyptian network connectivity from the outside world as well as 50–60% loss of outbound connectivity on the westbound route in India [2]. Similarly, another earthquake in Nepal in the year 2015 caused a lot of damage in the form of schools, houses, transmissions towers, and ICT access center collapsing as well as the failure of microwave and fiber backhaul links. This resulted in severe damage to both wired and the wireless communication links [3,4]. Another similar earthquake of 7.1 magnitudes recorded in central Mexico on September 19, 2017. In addition to 355 fatalities, 6100 injuries, and nearly 44,000 building destruction, this also devastated the communication infrastructure by damaging the underground optical fibers as well as the wireless infrastructure [5]. It has

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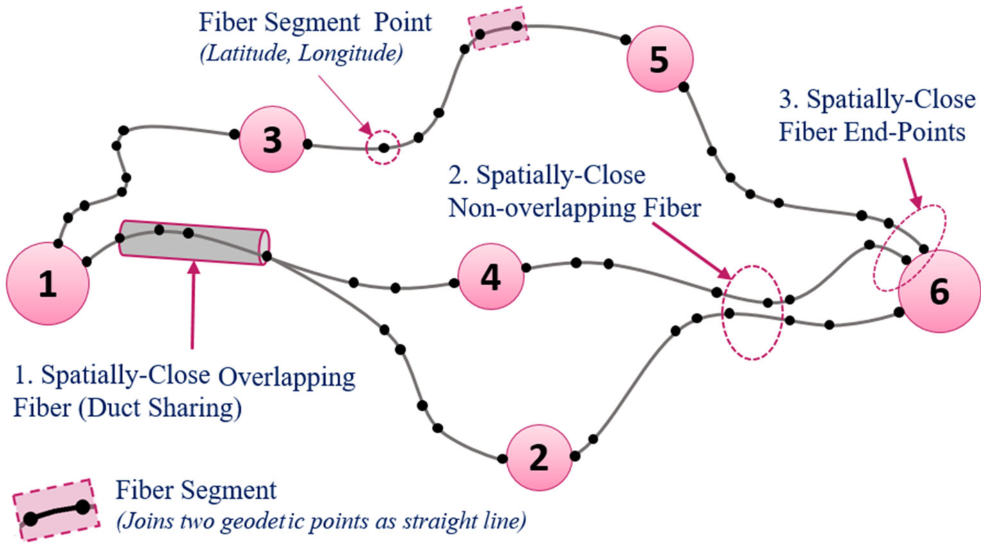


Fig. 1 Types of spatially close fibers

been estimated that such communication failures due to natural disasters lead to fiscal losses ranging from USD25000 to USD150000 per hour [6].

Although both the primary and the secondary paths between two network nodes are always disjoint, even then they may concurrently fail in the event of a large-scale disaster due to spatially close fibers [7]. This may happen due to many reasons that result in spatially close lightpaths. One reason for their closeness may be placing of multiple fibers in the same duct by the network operators to minimize the digging costs and thus reduce the capital expenditure (CAPEX) [8,9]. An example of spatially close overlapping fibers due to duct sharing is shown in Fig. 1. It is also possible that the fibers which are not in the same duct are also spatially close due to the close vicinity of their ducts. Another scenario of spatially close fibers may be the closeness of the fiber endpoints due to their termination at the same destination node. This may happen due to the infrastructural or geographical constraints. Disjoint lightpaths are physically separated but may fail simultaneously as their constituting fiber segments belonging to different fiber sets can be affected simultaneously in the event of a disaster due to spatial closeness. To overcome this problem and enhance the network survivability, the minimum spatial distance (MSD) of the disjoint lightpaths should be maximized. This will increase the network robustness against disaster-based failures as well as enable the network operators to ensure provisioning of services in the event of a large-scale disaster and thus minimize their fiscal losses.

Geographically, optical fibers are laid down in a non-straight manner between cities or across oceans because of the governing rules or the infrastructural and terrain constraints. These fiber lightpaths can be approximated as a concatenation of multiple fiber segments of varying lengths and can be mapped on geodetic coordinates (latitudes and longitudes) or be transformed into the corresponding two-dimensional Cartesian coordinate system. In this paper, we propose routing algorithms for (1) maximizing the minimum spatial distance between a disjointed pair of lightpaths, and (2) minimizing the path weight of the primary lightpath, while the minimum spatial distance between the lightpath pair is constrained. The rest of the paper is as follows: Section 2 discusses the related work. The problem formulation and our proposed routing algorithms are presented in Sect. 3. Simulation results are discussed in Sect. 4. Finally, the paper is concluded in Sect. 5.

2 Related Work

In fact, the disaster events are inevitable; however, their impact on the network services and their downtime can be significantly reduced by enhancing the network survivability [9,10]. This area has drawn the attention of the research community, and many studies have been conducted during the recent years. These studies have investigated the issue of disaster vulnerabilities in different perspectives like natural disasters, weapons of mass destruction attacks, electromagnetic pulse, region-aware and network augmentation to address the influence of regional failures [7,11–23]. Network geography can forecast the impact of a failure on network's services and capacity by assessing their cascading failures. Dikbiyik et al. [12] have proposed solutions to prevent connection failures from disasters through proactive approaches. Using proactive approach, the damages and cascading failures are estimated as specific events like hurricanes, floods, and earthquakes occurring in specific geographical locations. An interesting study by the Neumayer et al. [24] investigates the network robustness against geographical line segment and circular segment cuts. In [17], Neumayer et al. have presented the geographical-based failures as a generalized max-flow and min-cut problems. In this approach, a rival tries to reduce the network connectivity through multiple network attacks. To address the geographical min-cut problem, they proposed a polynomial-time algorithm and have presented several approaches to address the geographical max-flow problems. The physical infrastructure of the optical network is vulnerable to the weapon of mass destruction (WMD), physical attacks like an electromagnetic pulse (EMP), military bombing, or some kind of natural disaster. In [15,25,26], analysis of the network vulnerability under geographically correlated failures due to a physical attack has been addressed with different perspectives and probabilistic framework. In the disaster scenario, the probability of getting affected is very high for spatially correlated nodes (nodes which are confined to a region). This simultaneous failure of multiple nodes turns in disconnecting from a large spanning area of the network. Banerjee et al. in [27] proposed an approximation algorithm for a file distribution scheme to address this problem so that every node in the network can reconstruct the original file by retrieving $\mathcal{K}$ file fragments from other nodes surrounded by r hop neighborhoods with minimized storage. This file distribution scheme for a data storage network depends upon region-based fault in the network in contrast to [28–30].

Disaster-based failures may affect a part of the network confined to a certain geographical region in different ways. Their impact can be modeled by different shapes like circular, triangular, elliptical, or rectangular. Trajanovski et al. [31] studied the problem of finding the critical region of predetermined size and proposed a polynomial-time algorithm to identify the most vulnerable regions in a given network. They have also proposed a polynomial-time algorithm by considering the region-aware network to reduce the impact of regional failures in [18]. They proved that how region-disjoint path problem is NP-hard and proposed a heuristic algorithm for this problem. Since network nodes and fiber links in an optical network are deployed geographically, they must have geographical information (i.e., latitudes and longitudes as geodetic points). In [19], Iqbal et al. considered the geographical information of network nodes and links and included the idea of time-based disaster impact. They incorporated this information for finding the risk profile of different network areas for a series of time instants. The rationale behind this is that some disasters, like hurricanes, may traverse different network areas at different times. Then, they proposed polynomial-time algorithms to evaluate the vulnerability of network connections, which enables to find the most vulnerable network connections. Iqbal et al. [7] also proposed fast running algorithms to identify spatially close fibers and grouping them using the minimum number of distinct risk groups. In [20], Agrawal et al. proposed a Seismic Zone Aware Node Relocation (SZANR) scheme 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 by minutely changing the node location in the network topology. Awaji et al. introduced a new strategy in [21] for enhancing the network robustness against natural disasters (e.g., mega-quakes and tsunamis). They outlined the solutions for two imperative facets: survivability against damages in broad-area networks and quick network recovery in devastated areas. They proposed optical packet switching combined with circuit switching for more survivable broad-area networks, while emergency optical networks and hierarchical addressing are presented for quick network recovery in devastated areas.

Virtual network mapping can efficiently utilize computing and networking resources on the same physical network infrastructure. Virtual network services must be as resilient as possible to function even in the event of catastrophic disasters, intentional attacks, and fiber cuts. Galdamez et al. [22] studied the problem of resilient virtual network mapping and proposed a region-disjoint mapping algorithm for mapping the primary and backup virtual networks onto non-overlapping geographical area network, thus providing survivability against large-scale regional failures.

Sousa et al. [23] addressed a similar problem termed as 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 this problem. In the same context, Wang et al. [32] presented a geographical-aware route selection algorithm for finding alternative paths with appropriate geographical separation, referred to as the proximity factor. Contrary to the work of [23,32], our proposed algorithms are based on the Yen's algorithm [33], such that the running time and accuracy of our algorithm can be tuned through the selected value of K. ILP is often too time-consuming. Our proposed algorithms 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 algorithms always find the most optimal solution.

3 Problem formulation and proposed algorithms

Let an undirected graph $G(N, L)$ represent a physical network, where $N = \{n_1, n_2, n_3, \ldots, n_N\}$ is the set of $|N|$ nodes and $L = \{l_1, l_2, l_3, \ldots, l_M\}$ is the set of $|M|$ undirected links representing bidirectional optical fibers. The $P = \{P_1, P_2, P_3, \ldots, P_k\}$ is the set of shortest lightpath

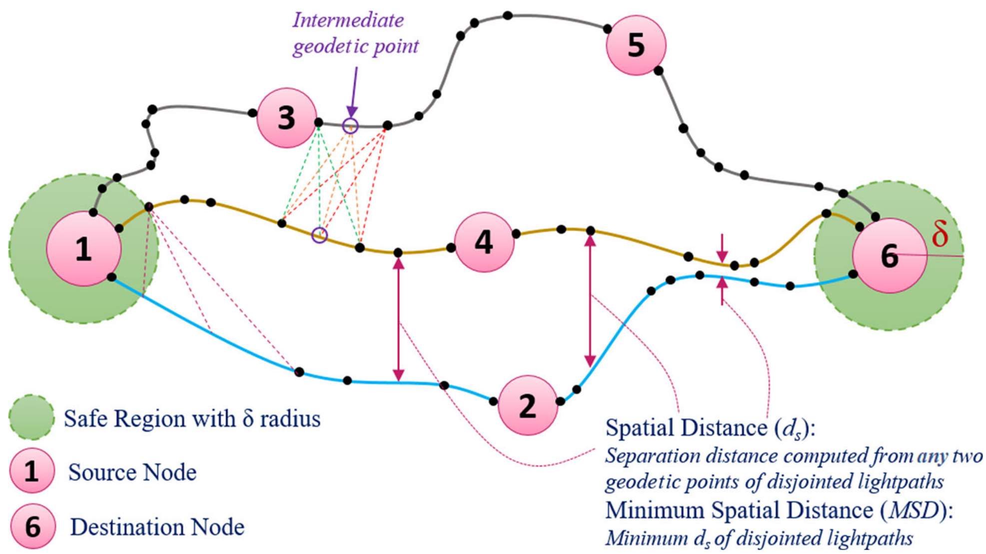


Fig. 2 Problem formulation

candidate from source node $\boldsymbol{s}$ to destination node $\boldsymbol{t}$ and $w = \{w_1, w_2, w_3, \ldots, w_k\}$ is the set of corresponding path weights, and $(P_u, P_v) \in \{P \times P\}$ represents the link-disjoint pair of lightpaths with corresponding path weight pair (w_u, w_v).

There are some assumptions we made to formulate the problem:

(i) Source and destination nodes are assumed safe from the impact of the disaster. Figure 2 shows the exclusion distance δ (in km) which is defined as the circular region for which the source node, destination node, and enclosed fiber parts are assumed to be safe. The value of δ can be less than the length of enclosed fiber segments.

(ii) Link-disjoint pair of lightpaths (P_u, P_v) means P_u does not share any $l \in L$ with P_v.

(iii) Spatial distance (d_s) is the separation distance (measured in km) and calculated from any two geodetic coordinates distinctively taken from two lightpaths between two network nodes. These geodetic coordinate might be the starting, ending, or intermediary point of fiber segments. Spatial distance is assumed as zero when fiber segments of two disjoint lightpaths overlap/intersect or primary and backup lightpaths share same nodes.

(iv) Minimum spatial distance (MSD) can be defined as the minimum d_s of two disjoint lightpaths.

3.1 Disjoint lightpath pair with maximized minimum spatial distance

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

$$\underset{d_s}{\text{Maximized}} \left\{ \underset{(P_u, P_v)}{\text{Minimized}} \left\{ d_{s1}, d_{s2}, d_{s3}, \ldots, d_{sk(k-1)/2} \right\} \right\} \tag{1}$$

Here, d_{si} is spatial distances for $(P_u, P_v) \in \{P \times P\}$. 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 $\boldsymbol{s}$ and $\boldsymbol{t}$ in the given network (using Yen's algorithm [33] as described in line 2). Other k-shortest path routing algorithm [34–41] 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 using Algorithm B. If pair (P_u, P_v) is link-disjointed, then the corresponding minimum spatial distance "msd or MSD" and the average minimum spatial distance "msdAvg" of the pair are computed in line 7 using Algorithm C (a modified form of the algorithm proposed in [7] to detect spatially close fibers, based on kD tree and k nearest neighbor or kNN search [42–44]). The processing theme of Algorithm C is as follows:

(i) All geodetic coordinates of nodes and starting, ending and intermediary points of fiber segments of P_v are inserted in kD tree excluding the fiber segments and nodes which are in safe region.

(ii) A set X of geodetic coordinates of nodes and starting, ending and intermediary points of fiber segments of P_u are constructed.

(iii) Now iterate point by point in X (suppose β) to find the nearest-neighbor point (suppose ƙ) in kD tree using kNN search, and compute the spatial distance between β and ƙ and store in the set D.
(iv) Return the minimum value from set D that will be the required MSD of pair (P_u, P_v).

In some cases, multiple link-disjoint pairs can have the same MSD value. Hence, we introduce another supporting decision variable, the "msdAvg" that represents the quantitative disjointness between the lightpaths, as a tiebreaker. Lines 8–11 select the link-disjoint pair of lightpaths based on msd and msdAvg values with maximized MSD. For geo-calculations over a great circle (i.e., finding distance, midpoint, intermediate point, etc.) between latitudes and longitudes of two geodetic coordinates, we used the formulae given in [45]. We also exclude certain fiber parts according to exclusion distance. The MSD will start measuring after exclusion distance.

3.2 Disjoint lightpath pair with minimum primary lightpath weight and constrained minimum spatial distance

Provisioning of Disjoint Pair with Minimum Primary Lightpath and Constrained Minimum Spatial Distance (DPMPLW) Problem: Find a pair of link-disjoint lightpaths (P_u, P_v) such that the path weight w_u of the primary lightpath P_u is minimized while the minimum spatial distance (MSD) is constrained by a value α.

$$\underset{d_s}{\text{Maximized}}\left\{\underset{(P_u,P_v),ds\le\alpha}{\text{Minimized}}\{w_1, w_2, w_3, \ldots, w_k\}\right\} \tag{2}$$

We proposed the DPMPLW algorithm in the context of the mentioned problem. The algorithm is divided into two parts, with the first part similar to our earlier DPMMSD algorithm. Lines 3–11 find the desired disjointed lightpaths pair with minimum path weight, and the MSD will be constrained by α. Very large α can represent natural disasters, and small α can represent construction-level failures.

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*, geodetic locations data in the form of (x_1, y_1) and (x_2, y_2) for each fiber segment and excluding Distance (δ) from ***s*** and ***t*** nodes.

Output: A pair of link-disjoint lightpaths with maximized minimum spatial distance.

1: *mmsd* **:=** -1, *mmsdAvg* **:=** -1 i.e. Initializing decision variables
2: Find *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 given in appendix (Algorithm-A).
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 given in appendix (Algorithm-B).
6:   **if** *pair* (P_u, P_v) **not** *matched* i.e. disjointed pair
7:   [*msd*, *msdAvg*] **:=** Computing the minimum spatial distance and average minimum the spatial distance between disjoint pair (P_u, P_v) using algorithm given in appendix (Algorithm-C).
8:   **if** *mmsd* <= *msd* **and** *mmsdAvg* <= *msdAvg*
9:   *mmsd* **:=** *msd*
10:   *mmsdAvg* **:=** *msdAvg*
11:   *ConstrainedPair* **:=** (P_u, P_v)

Algorithm 2: *Disjoint Pair with Minimum Primary Lightpath and Maximized Minimum Spatial Distance (DPMPLW)*

Input: An adjacency matrix G of the network, source node s, destination node t, desired number of shortest paths K, geodetic location data in the form of (x_1, y_1) and (x_2, y_2) for each fiber segment, excluding Distance (δ) from s and t nodes and an MSD constraint α.

Output: A pair of link-disjoint lightpaths with minimized primary lightpath and constrained MSD.

mmsdAvg **:=** -1, *minWeight* **:=** ∞
Find 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 given in appendix (Algorithm-A).
for *u* **from** 1 **to** *K-1*
  for *v* **from** *u+1* **to** *K*
    matched **:=** LinkMatching (P_u, P_v) algorithm given in appendix (Algorithm-B).
    if *pair* (P_u, P_v) **not** *matched* i.e. disjointed pair
      [*msd*, *msdAvg*] **:=** Computing the minimum spatial distance and average minimum the spatial distance between disjoint pair (P_u, P_v) using algorithm given in appendix (Algorithm-C).
      if *msd* < α and *mmsdAvg* <= *msdAvg*
        if *minWeight* > w_u
          minWeight **:=** w_u
          mmsdAvg **:=** msdAvg
          ConstrainedPair **:=** (P_u, P_v)

3.3 Complexity analysis

Finding the disjoint pair of paths in undirected graphs is an NP-hard [46,47]. The upper bound time complexity of Yen Algorithm is $O(KN^3)$ [33] where K is the number of shortest paths and N is the number of nodes. For small values of K, several related problems are shown to be NP-complete [46,48,49]. If we take very large values of K, the computing time will increase linearly including impact of number of links and their segments. For unbounded value of K, all shortest paths will be discovered by Yen's algorithm and so do disjoint pairs of lightpaths. Subsequently, the proposed algorithms will act as exact otherwise heuristics. Algorithms can modestly discard the processing of lightpath pairs having zero MSD, and solution may converge to polynomial time. The worst-case time complexity of both of our proposed algorithms 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 simulated the performance of our algorithms using the European network, US network, and the random Erdős–Rényi and Watts–Strogatz networks. The Erdős–Rényi [50] networks have a fixed number of nodes with a random but equally likely number of edges. However, the Erdős–Rényi networks lack two essential characteristics witnessed in many real-world networks: do not have high clustering coefficients and do not account for the formation of hubs, whereas real-world networks are scale-free and obey power law for degree distribution [51]. The Watts–Strogatz networks address these two limitations, by exploiting small world properties. It has high clustering coefficient while retaining the short average path lengths of the Erdős–Rényi networks, by interpolating between the Erdős–Rényi network and a regular ring lattice [52]. The purpose of using random graph generators is to analyze the performance and efficiency of algorithms for probabilistic construction of networks with large girth and chromatic number while varying different parameters such as shortest paths (K), exclusion distance from the source and destination nodes (δ), number of nodes and links and separation distance (α). In a real-life network, the performance of the proposed algorithms with increasing number of nodes and links was not possible to evaluate. Both algorithms are 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 averaged over 1000 runs.

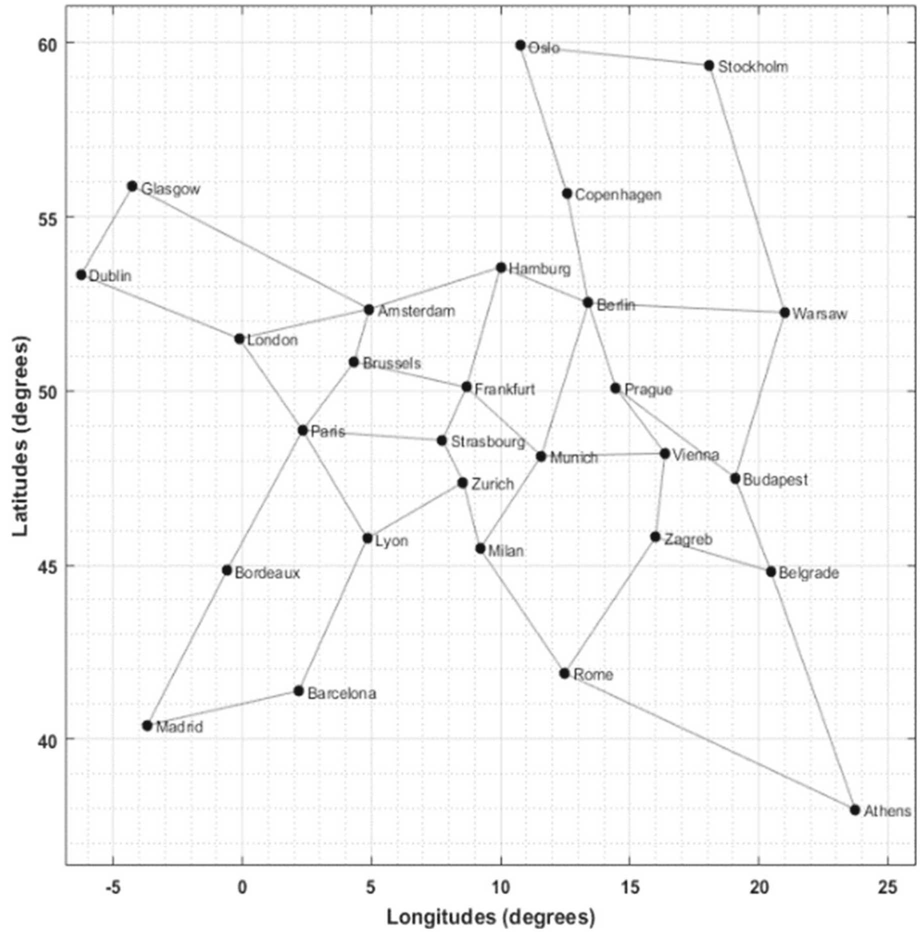


Fig. 3 Geographically mapped European network

Figures 3 and 4 show a geodetic representation of the European network [53] and US Network [54], respectively, where nodes are mapped as per corresponding geodetic coordinates (latitudes and longitudes) in degrees. Figures 5 and 6 depict the examples of the MSD between two lightpaths on the European and US networks, respectively. Red and blue colored paths indicate the primary path and backup path of the disjoint pair, respectively.

Figure 7a shows the declining impact of δ on the computing times for our proposed algorithms in European network. As we increased δ, more fiber segments are ignored from the measurement of MSD and reducing the computation time. Similarly, δ also affects the MSD as shown in Fig. 7b. When δ is increased to a certain value, then the MSD becomes constant.

The effect of the number shortest paths (K) on the computation of disjoint pairs and path lengths for both algorithms is shown in Fig. 8. The total number of disjoint path pairs depends on the total nodes and fiber links within the network. Figure 8b shows the variation of primary and backup path lengths by changing K of both algorithms. DPMMSD provisioned a disjoint lightpath pair without considering path lengths, while DPMPLW provisioned a disjoint lightpath pair with minimum primary path length.

During simulation, it was observed that most of the running time is consumed at finding and computing disjoint path pairs and their spatial distance. Figure 9 shows the K-Time graph for European network using our proposed algorithms. The processing time rises almost linearly when K is increased. For the European 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. The K-Time graph shows that both of our proposed algorithms have almost the same computation time.

Input parameters like rewiring probability and node degrees have been fixed to 1 and 2, respectively, for both network generators. If node positions are assumed to follow a Poisson process in the geographical plane with the scaled Lebesgue mean measure, we can get node positions as geodetic points using bounds of a 4-dimensional vector in the form $[x_{min}\ x_{max}\ y_{min}\ y_{max}]$ for a confined region. Through these positions, fiber links and their segments were generated with rewiring probability as 1 and node degree as 2 for both network generators. For random networks, links cannot be

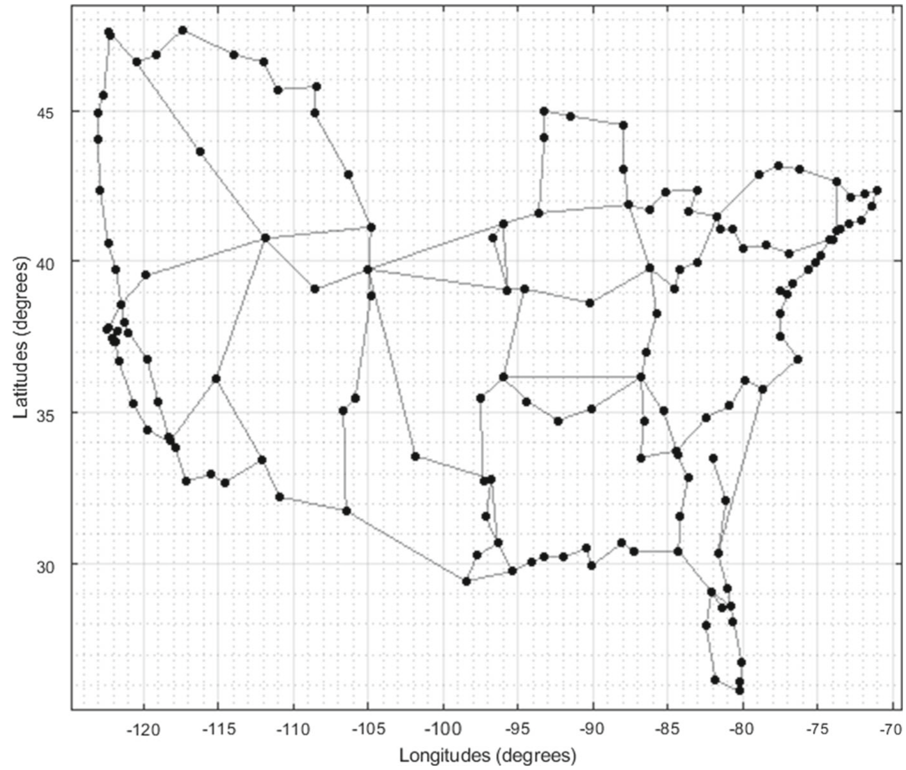


Fig. 4 Geographically mapped US network

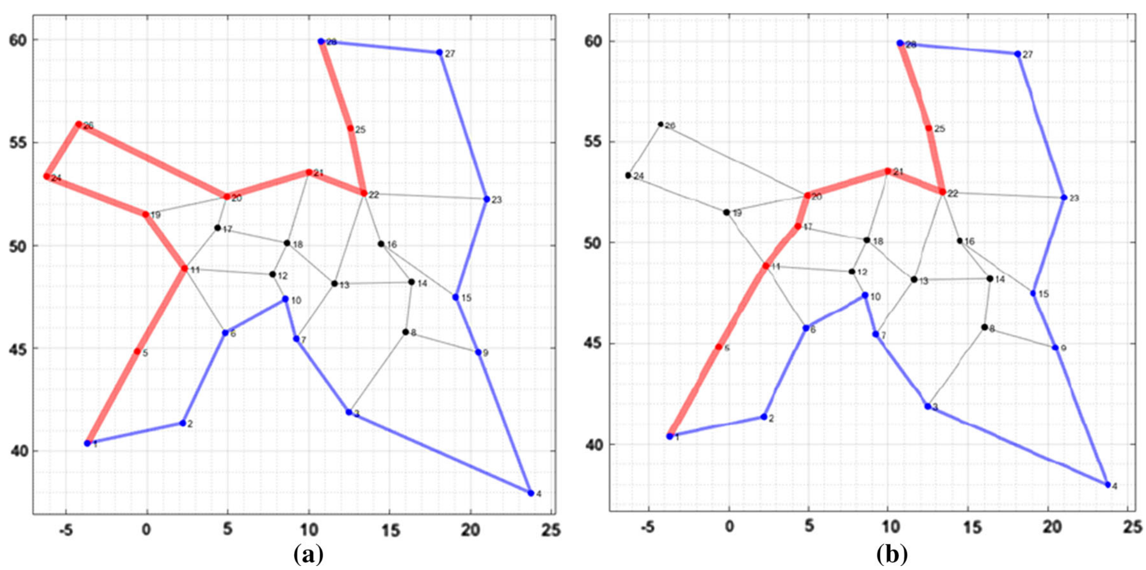


Fig. 5 Provisioning of disjoint pair of lightpaths in European network. **a** Graph of pair (DPMMSD) with MSD = 223.42 km. **b** Graph of pair (DPMPLW) with MSD = 223.42 km

generated as curved or zigzag form; however, we assumed if fibers are laid down on earth for a long distance, then it can be curved, and we can divide it as two segments. Further, geo-intermediary points and the distance between these points were calculated over a great circle. Figures 10 and 11 graphically describe the performance of DPMMSD and DPMLPW on Erdős–Rényi and Watts–Strogatz networks, respectively. Networks are generated for nodes $N = \{10, 15, 20, \ldots, 50\}$ with links generated randomly using Poisson distribution. The value of K is taken as 1000, and the source and destination nodes are arbitrarily selected. It was observed that the number of disjoint pairs generated and computing times against nodes of Watts–Strogatz are more than that of Erdős–Rényi networks.

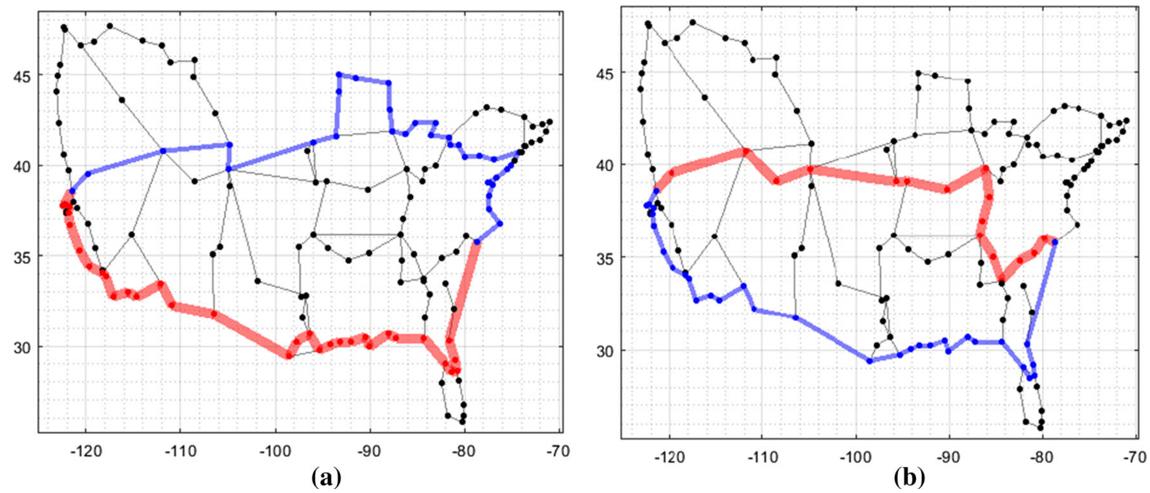


Fig. 6 Provisioning of disjoint pair of lightpaths in US network. **a** Graph of pair (DPMMSD) with MSD = 9.52 km. **b** Graph of pair (DPMPLW) with MSD = 6.59 km

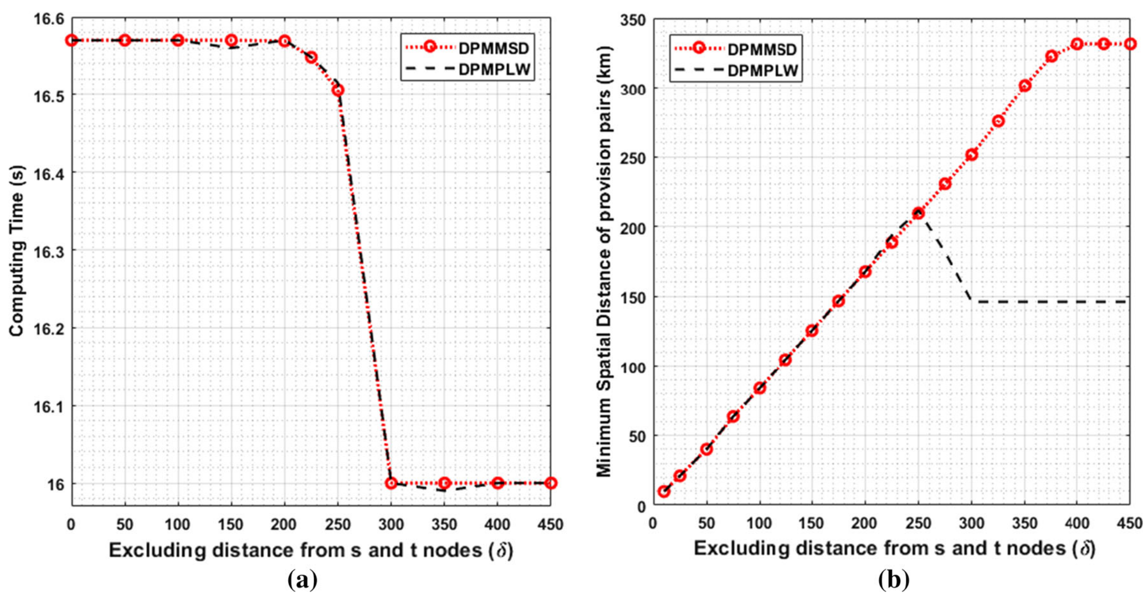


Fig. 7 Effect of excluding distance on computing time and MSD. **a** Excluding distance versus computing time. **b** Excluding distance versus MSD

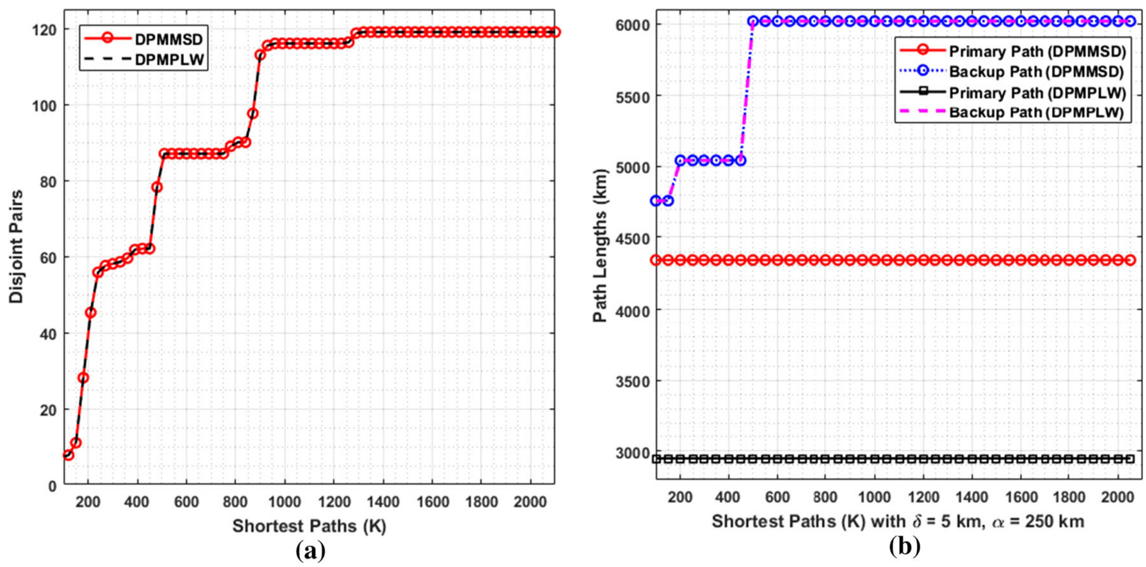
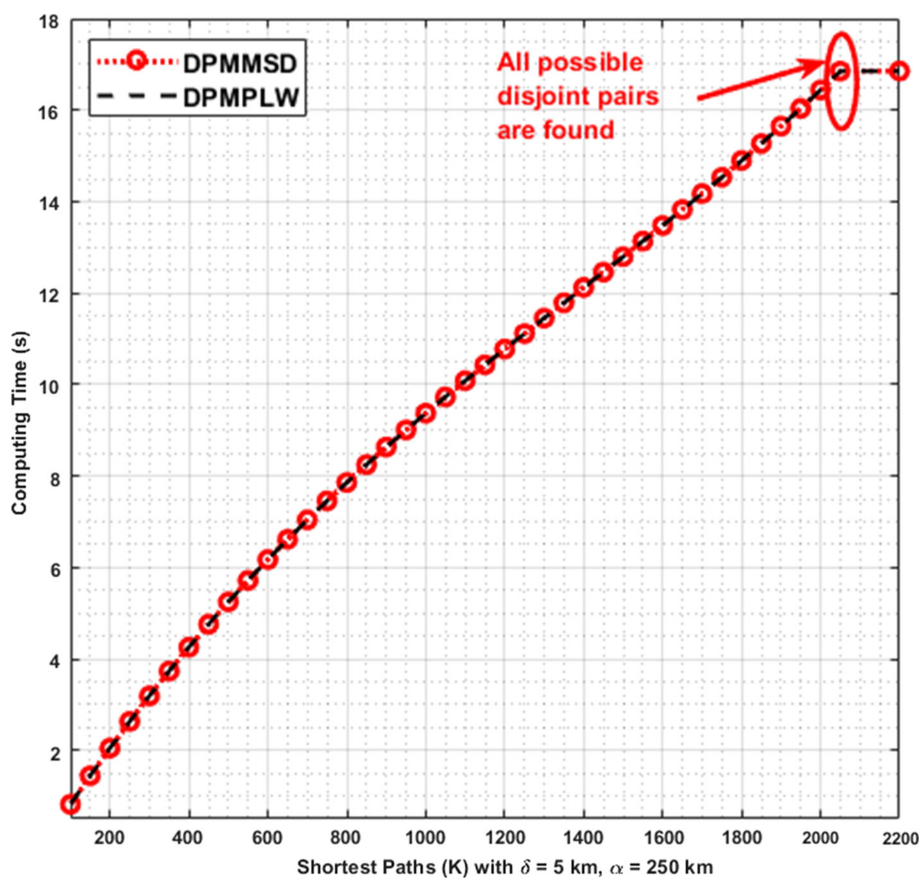


Fig. 8 Effect of K on computation of disjoint pairs and path lengths when $\delta = 5$ km, $\alpha = 250$ km. **a** Shortest paths versus disjoint pairs. **b** Shortest paths versus path lengths

Fig. 9 Effect of K on computing time when $\delta = 5$ km, $\alpha = 250$ km



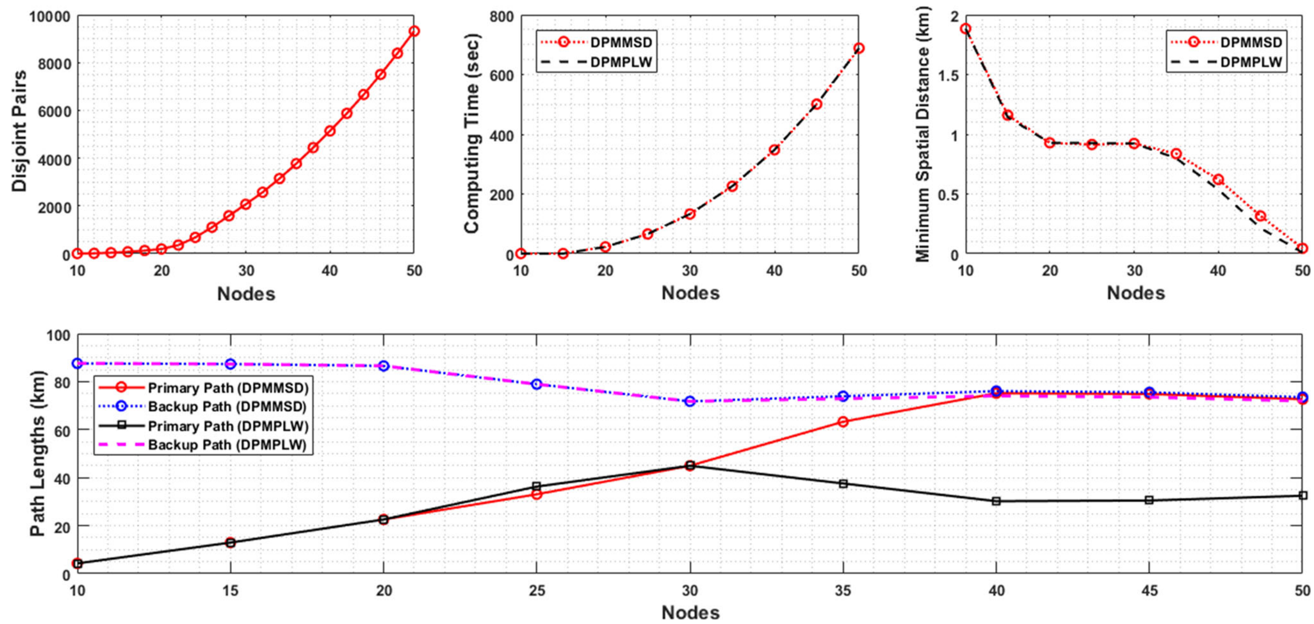


Fig. 10 Performance evaluation of DPMMSD and DPMLPW on Erdős–Rényi networks

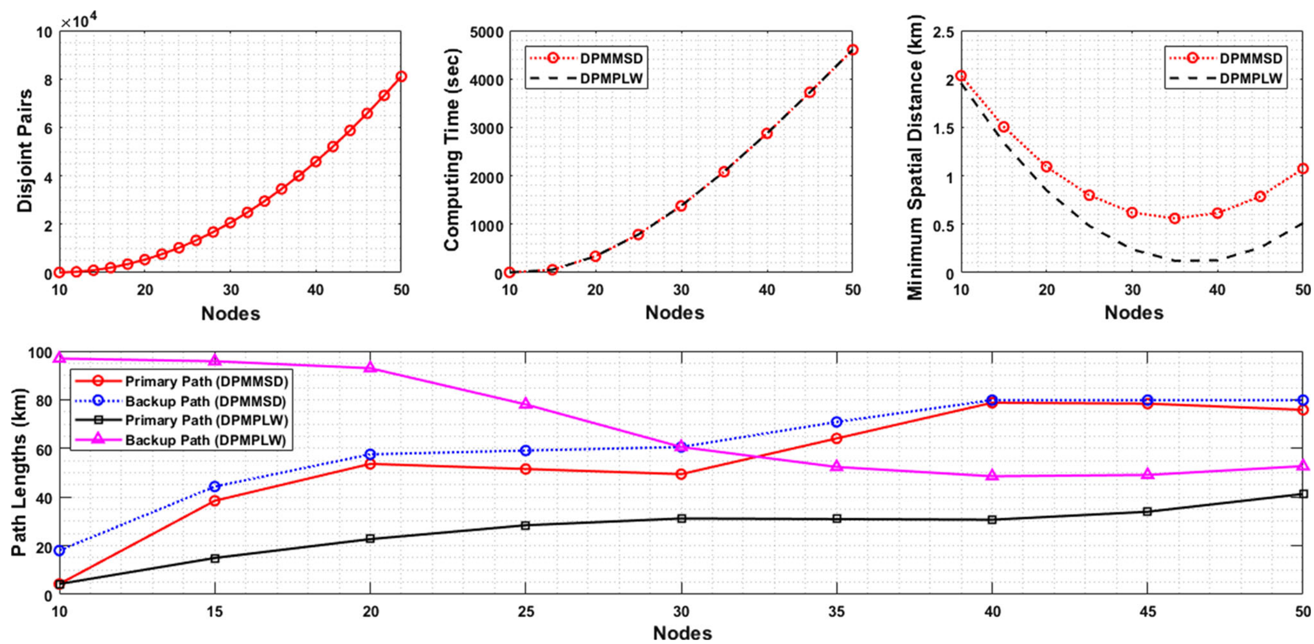


Fig. 11 Performance evaluation of DPMMSD and DPMLPW on Watts–Strogatz networks

5 Conclusions and future work

In this paper, we have proposed two routing algorithms for provisioning a pair of link-disjoint lightpaths between two network nodes. Our first algorithm finds a pair of lightpaths with a maximum value of minimum spatial distance, while our second algorithm finds a pair of lightpaths with the path weight of primary lightpath minimized and constrained minimum spatial distance. Through simulation, we have shown that our first algorithm can increase network survivability against spatial-based concurrent fiber failures, albeit with higher path weights. Alternatively, our second algorithm put a constraint on the minimum spatial distance between the pair of lightpaths, while achieving the minimum path weight possible for the primary lightpath. We have also tested our algorithms using real-life optical network topologies, and two types of random network topologies.

In our future work, we will provide an exact solution using integer linear programming (ILP) and do a comparison with our proposed approach.

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Appendix

Algorithm-A: *Yen's K-Shortest Path Algorithm*

Input: An adjacency matrix G of the network, source node $\boldsymbol{s}$, destination node $\boldsymbol{t}$ and the desired number of shortest paths K.

Output: Sets of paths $P = \{P_1, P_2, P_3, \cdots, P_k\}$ and weights $w = \{w_1, w_2, w_3, \cdots, w_k\}$.

1: $[P_1, w_1]$ **:=** Shortest path and weight from *s* to *t* using Dijkstra Algorithm
2: tempG **:=** G
3: for *k* from 2 to *K*
4:   **for** *i* **from** 1 **to** size (P_{k-1}) - 1
5:   currentNode **:=** $P_{k-1}(i)$
6: $[R_i, w_{si}]$ **:=** The sub-path and sub-weight from *s* to *currentNode* using Dijkstra Algorithm
7:   **for** *j* **from** 1 **to** *k* - 1
8: $[R_j, w_{sj}]$ **:=** The sub-path and sub-weight from ***s*** to P_j using Dijkstra Algorithm
9:   **if** $R_i == R_j$
10:   *nextNode* **:=** $P_j(i+1)$
11:   tempG (*currentNode*, *nextNode*) **:=** ∞
12:   Make the *currentNode* unreachable
13: $[S_i, w_{ci}]$ **:=** Shortest path and weight from *currentNode* to ***t*** using Dijkstra Algorithm
14: $[X_i, w_i]$ **:=** $[R_i + S_i, w_{si} + w_{ci}]$
15: $[P_k, w_k]$ **:=** Shortest path amongst all paths in *X*
16:   tempG **:=** G

Algorithm-B: *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*.

matched := false
for each fiber links e_{P_u} in lightpath P_u
    for each fiber links e_{P_v} in lightpath P_v
        if $e_{P_u} == e_{P_v}$
            matched := *true*
            return

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

Input: A pair of link-disjoint lightpaths ($P_u = \Sigma_1^i L_{ui}$, $P_v = \Sigma_1^j L_{vj}$) 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. Excluding distance (δ) for which the source node, destination node and enclosed fiber parts are assumed safe.

Output: Minimum spatial distance (MSD) and the average minimum spatial distance between the lightpaths of pair (P_u, P_v).

Suppose for the lightpaths P_u *and* P_v, *msd* := ∞, *totalPoints* := 0, *msdSum* := 0, *msdAvg* := 0
for each fiber L_{vj}
    for each segment l_v
        Compute the segment midpoint m_{l_v} apart δ from source and destination node segments (for these segments compute points at δ). Insert fiber segment joining points (x_{v1}, y_{v1}), (x_{v2}, y_{v2}), points at δ and m_{l_v} into the k-d tree *Q*.
for each fiber L_{ui}
    for each segment l_u
        Compute the segment midpoint m_{l_u} apart δ from source and destination node segments (for these segments compute points at δ).
        Find nearest neighbor distance *{d₁, d₂, d₃}* of points (x_{u1}, y_{u1}), (x_{u2}, y_{u2}) and m_{l_u} or point at
        δ using kNN search and k-d tree *Q, however,* ignore the source and destination nodes.
        d := minimum of $\{d_1, d_2, d_3\}$
        if *msd* > *d*
            msd := *d*
            msdSum := *msdSum* + *d*
            totalPoints := totalPoints + 1
msdAvg := msdSum / totalPoints

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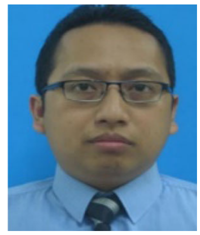

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