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Disaster-resilient lightpath routing in WDM optical networks

M. Waqar Ashraf[1] · Rizwan Aslam Butt[2] · M. Faheem[3] · M. Tariq[4] · Abid Munir[4]

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Abstract

Optical network serves as a core network with huge capacity and a multitude of high-speed data transmission. Natural disasters and physical attacks showed significant impacts on the optical networks such as damages the network nodes and optical links. Network survivability attempts to provide uninterrupted services when network component ceases to function or malfunctioned either in the event of a disaster or due to human intervention. In this paper, two polynomial-time algorithms have been proposed to select an optimal pair of link-disjoint lightpaths between two network nodes such that (1) their minimum spatial distance (MSD) is maximized, and (2) the path length of the primary lightpath is minimized such that backup lightpath has some particular MSD from the primary lightpath while disregarding safe regions around the source and destination nodes. Through extensive simulations, it is shown that, in case of disaster event, the first algorithm (DPMMSD) computes the backup path with maximum survivability in case of multiple link failures of spatially close nodes, whereas second algorithm (CMMSD) computes the shortest backup lightpath while adhering to the target survivability requirements. DPMMSD, CMMSD and the benchmark EKSP enables the evaluation and comparison of the performance. EKSP computes more pairs hence takes more computing time whereas DPMMSD and CMMSD modestly discard the computation of self and repeating pairs, enabling quick computations.

Keywords Lightpath routing · Network survivability · Minimum spatial distance · Optical network

1 Introduction

Optical networks serve as backhaul to all modern telecommunication networks and offer reliable transmission of data in huge volumes over long distances. Optical networks are much faster with low attenuation compared to other technologies like copper-based digital

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✉ M. Waqar Ashraf
waqarashraf@bzu.edu.pk

[1] Department of Computer Engineering, Bahauddin Zakariya University, Multan, Pakistan

[2] Department of Telecommunication Engineering, NED University of Engineering & Technology, Karachi, Pakistan

[3] Department of Computer Engineering, Abdullah Gul University, Kayseri, Turkey

[4] Department of Electronics Engineering, Islamia University, Bahawalpur, Pakistan

subscriber line (DSL) and wireless networks. The undersea optical fiber cable network that traverses through the globe and comprises of 366 cables with 1.2 million kilometres length and 1,006 landing stations (TeleGeography 2018). These cables provide nationwide connectivity between the dense wavelength division multiplexing (DWDM) gateway nodes over very long distances such as the Asia-America gateway (AAG) cable system is 20,000 km long (Asia-America Gateway (AAG) 2018). The shortest link is 131 km long i.e. the Celtix Connect connecting UK and Ireland (Submarine Cable: Celtix Connect 2018). These optical links carry huge amount of traffic especially the newer cables (made of new fiber materials installed with newly developed amplifiers) can carry Tbps of data as compared to older cables. For instance a MAREA cable (Submarine Cable: MAREA 2018) can carry 160 Tbps. Therefore, survivable routing in these networks is very important.

The main drivers of this rapid growth in worldwide connectivity and the proliferation of Internet-connected devices are the increasing trends of cloud computing and emerging social IT needs e.g., social media apps, video streaming, changing business conducts etc. This revolution has led to the immense growth of global IP traffic. Forecasted global IP traffic growth (Cisco 2017) from 2016 to 2021. It is estimated that annual global IP traffic will be 3.3 ZB at a Compound Annual Growth Rate (CAGR) of 24% from 2016 to 2021 which is nearly threefold in five years. Projected values of the world population that will be using internet and monthly internet traffic data per user will be 58% and 61 GB respectively by 2021. It is anticipated that eighty percent of the internet traffic will be video streaming with average broadband speed of 53 Mbps.

Statistics implicating cable damage for smaller outages that occur nationwide are not exactly available. However, hundreds of cables cut related network outage notifications will be returned if a phrase "cable cut" is searched through any internet search engine. Network outages due to fiber cut reported to Federal Communications Commission (FCC) from 1993 to 2001 were estimated to be 386 or 25% of all network outages. The outage for 30 min or more may affect over 30,000 customers (Hoffman 2018). Optical fiber cables, where each cable may carry hundreds of fiber strands made of doped glass, are enfolded with multiple layers of insulations. Fiber cables are laid down in bundles swathed by a duct between nodes (i.e., network equipment or part of equipment which serve different functions such as routing, switching and traffic grooming). Fiber cut occurs when a duct is cut due to fishing, anchoring, mudslide, earthquakes etc. All the lightpaths that traverse a failed fiber will be disrupted. A fiber cut or a duct cut can lead to tremendous data loss.

Despite both primary and backup lightpaths are always disjointed and being physically distant; these might still simultaneously fail due to a large-scale disaster event if fiber cables of these lightpaths are spatially-close (Ashraf et al. 2018). There are many reasons for which lightpaths can be spatially-close. One reason is duct sharing, multiple optical fiber cables laid in the same duct by the network service provider, in order to minimize cost of underground digging (BT reveals pricing proposals for duct and pole access 2017; Asplund et al. 2008; Beschorner 2018). Figure 1 shows such a scenario of spatially-close optical fibers sharing a common duct.

It is also conceivable that optical fibers which are actually not laid in a common duct may also be spatially-close because of their ducts being physically close. This may happen mainly on the sides of main roads and bridge crossings due to lesser space availability for laying the ducts for long haul communication. Another scenario of spatially-close fibers is the closeness of the fiber end-points due to their termination at the same destination node. Thereby, spatial distance between the disjointed lightpaths should be considered in order to enhance the network survivability. In this context, two polynomial-time algorithms have been proposed to select an optimal pair of link-disjoint lightpaths between two network

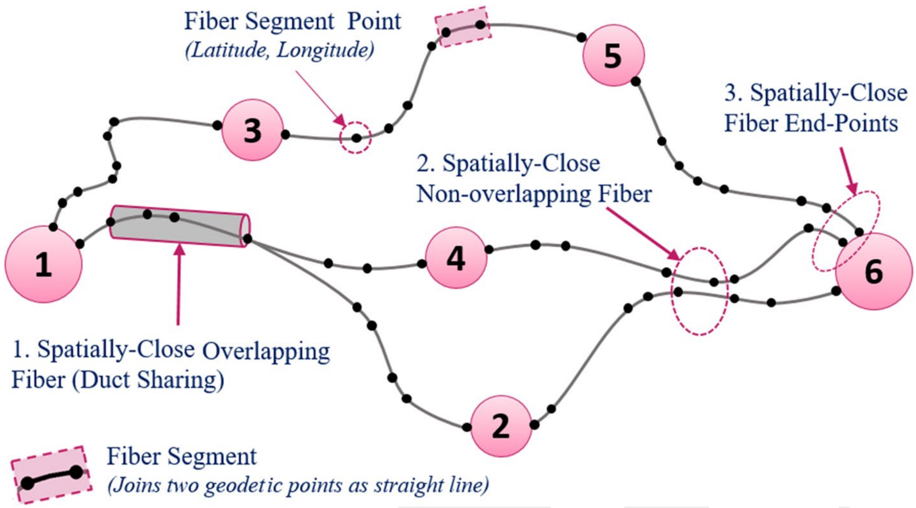


Fig. 1 Types of spatially-close fibers

nodes such that (1) their minimum spatial distance (MSD) is maximized, and (2) the path length of the primary lightpath is minimized such that backup lightpath has some particular MSD from the primary lightpath while disregarding safe regions around the source and destination nodes. Through extensive simulations, it is shown that the first algorithm shows excellent performance in terms of survivability in backup path computation by maximizing the distance between the primary and backup paths, in case of multiple link failures. Whereas, second algorithm optimizes the spatial distance between the lightpaths by choosing the shortest route while still adhering to the target survivability requirements.

2 Background and related work

Optical networks serve as backhaul to all modern telecommunication networks and offer reliable transmission of data in huge volumes over long distances. Optical networks are much faster with low attenuation compared to other technologies like copper-based digital subscriber line (DSL) and wireless networks. Network survivability attempts to provide continuous services in the event of network component ceases to function or malfunctioned. Natural disasters and physical attacks causes network to fail which significantly impact the services provided by the optical networks. Taming the awareness of networks to disaster risk constraints (Ferdousi et al. 2013) is becoming a key issue due to the rising risk of disasters. For network planning and management tools are required as given in Das et al. (2016). Separate tools are required for network optimization (as used in Le et al. 2017) to mitigate the effect of failures occurred due to a disaster event especially for spatially correlated failures in optical networks. A geographic information system (GIS) based fiber tool provides risk-aware new fiber network planning and seamless management of intact infrastructures (Matrood et al. 2014). During the recent years, research community conducted a lot of work to address the network disaster vulnerabilities with diverse perspectives (Ashraf et al. 2018, 2019; Neumayer and Modiano 2010; Kumari et al. 2020; Butt et al. 2018, 2019;

Mukherjee et al. 2014; Trajanovski et al. 2015; Hai 2019; Agrawal et al. 2017; Awaji et al. 2017; Galdamez and Ye 2017).

In the recent years, the focus of research community has been shifted to a new paradigm in building disaster-aware networks due to the growing number of disasters around the world. Disaster-resilience in network design enables to survive with maximum availability after disasters. Network infrastructure can be damaged by disasters directly or indirectly. The nature of damage may depend on the disaster type and impact. Fiber cut or equipment damage may be considered as direct impact whereas power outages and huge generated traffic (also known as post-disaster traffic floods) due to disasters can be considered as the indirect consequences.

Now-a-days, there has developed a lot of interest in determining the networks capability to survive from geographically correlated failures. A number of parameters have been showing up in the literature to enumerate the effects of these failures. In Long et al. (2014), Long et al. proposed the use of weighted spectrum to evaluate network survivability regarding geographically correlated failures. Additionally, they conducted a comparative analysis using other common survivability measures and weighted spectrum and solved an optimization problem for determining the most vulnerable geographic nodes and cuts. The impact of failure events on network's services and capacity can be determined from the network geography.

The key contributions compared to the previous works are (i) selection of disjoint lightpath pairs on the basis of minimum spatial distance instead of Euclidian distance which enables the direct implementation of this work, (ii) introducing the concept of self and repeating lightpath pairs, in Sect. 3, in order to reduce the computation overhead and (iii) employing the KD-tree which is a space partitioned data structure organizing points in two dimensions as well as k-nearest neighbour search (knows as KNN) to compute the minimum spatial distances.

3 Problem formulation and proposed algorithms

Let an undirected graph $\mathcal{G} = (N, L)$ representing a physical network, where $N = \left\{n_1, n_2, n_3, \cdots, n_{|N|}\right\}$ is the set of $|N|$ nodes and $L = \left\{l_1, l_2, l_3, \cdots, l_{|L|}\right\}$ is the set of $|L|$ undirected links representing bidirectional optical fiber cables. The $P = \left\{P_1, P_2, P_3, \cdots, P_k\right\}$ is the set of candidates as shortest lightpaths from source node s to destination node d and $W = \left\{W_1, W_2, W_3, \cdots, W_k\right\}$ 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 lightpath weight pair $\left(W_u, W_v\right)$. Link-disjoint pair of lightpaths (P_u, P_v) means P_u does not share any link $l \in L$ with P_v. It is assumed that Source and destination nodes are safe for a predefined value known as exclusion distance (δ), measured in kilometers. Figure 2 indicates that node (source or destination) and the fiber cables enclosed within the circular region of radius δ are assumed to be safe too. Spatial distance ($\mathrm{d_s}$) is the shortest separation distance measured in kilometers, from a particular geodetic coordinate of to any geodetic coordinate of link-disjoint lightpath. These geodetic coordinates might be the starting, ending, or intermediary point of the fiber segments.

Spatial distance ($\mathrm{d_s}$) is determined as separation distance between two disjoint lightpaths. Every lightpath is constituted from their own fiber cables set connecting source and destination nodes. Every fiber segment if presumed to be a straight line, then three geodetic points (start, end and intermediary points) on each fiber segment could have

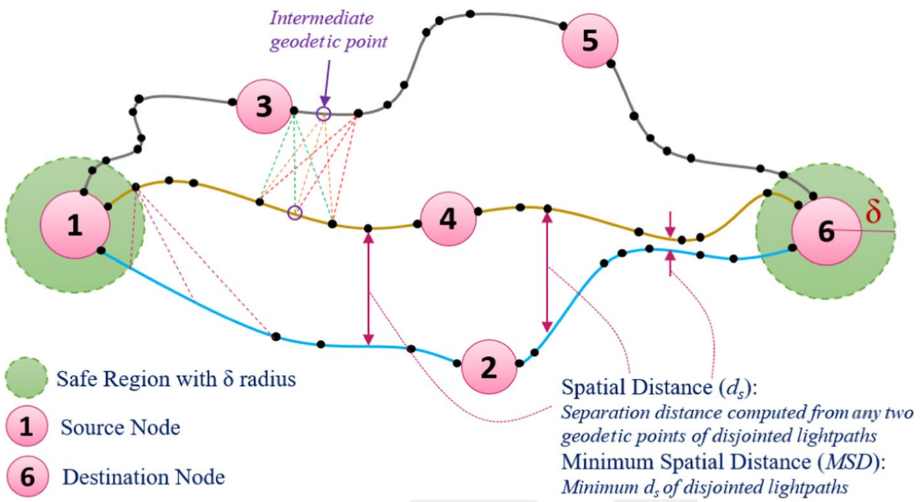


Fig. 2 Problem formulation

been used to compute d_s as indicated in Fig. 2. Minimum spatial distance (MSD) can be defined as the minimum ds between two disjoint lightpaths. Mathematically, suppose $\{d_{s1}, d_{s2}, d_{s3}, \cdots, d_{s\Lambda}\}$ are the distance computed for two link-disjoint lightpaths P_u and P_v, then MSD can be selected as prescribed below:

$$MSD_{(P_u,P_v)} = min\{d_{s1}, d_{s2}, d_{s3}, \cdots, d_{s\Lambda}\} \tag{1}$$

where

$$\Lambda = 1 + 2\sum S_{l_i} \tag{2}$$

Such that $l_i \in P_u$ is the total number of spatial distances between P_u and P_v,and S_{l_i} is the number of fiber segments per ith fiber link. The following scenarios need to be considered when computing the MSD between two lightpaths:

i. $\{P \times P\}$ holds candidate pairs including self and repeating pairs. Self-pair refers to the pair containing same lightpath that has been affected by the disasters and having zero MSD whereas repeating-pair is the pairs that occurs twice in $\{P \times P\}$. Figure 3 indicates all types of pairs for . Self and repeating pairs can be ignored to enhance the performance of algorithms.
ii. Spatial distance is considered as zero when fiber segments of two disjoint lightpaths either overlap or the backup and the primary paths share the same nodes.

3.1 Disjoint lightpath pair with maximized least spatial distance problem

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.

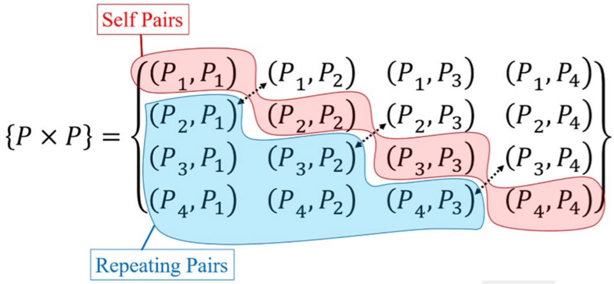


Fig. 3 Self and repeating pairs

$$Constrained\ Pair \leftarrow \max_{(P_u,P_v)} \left\{ MSD_{(P_u,P_v)} \right\} \tag{3}$$

DPMMSD algorithm is proposed to find the link-disjoint pair with maximized minimum spatial distance. For simplicity, DPMMSD can be divided into two parts. The first part of the algorithm finds K number of shortest paths between nodes **s** and **d** in the given network using Yen's algorithm (Yen 1971) as described at line 2. Another K-shortest path routing algorithm from Ardon and Malik (1971), Tsukiyama et al. 1976, Mehlhorn et al. 1987, Ahuja et al. 1990, Eppstein 1998, Santos 2007, Aljazzar and Leue 2011, Guo 2016) may also be used instead of Yen's algorithm. The second part of the algorithm proceeds through lines 3–15. Two nested for loops at lines 3 and 4 are initialized in such a way that self and repeating pairs are excluded. Line 5 confirms whether a pair (P_u, P_v) of shortest lightpaths is link-disjoint using Algorithm-B. If pair (P_u, P_v) is link-disjoint referring to line 6, then corresponding *MSD* and average minimum spatial distance *MSDAvg* of the pair is computed at line 7 using Algorithm-C (a modified form of the algorithm proposed in Ashraf et al. (2018) to detect spatially-close fibers). Algorithm-C used KD-tree and k-nearest neighbour or KNN search (Bentley 1975; Friedman et al. 1977; Panigrahy 2008) technique to find accounting the variables *MSD* and *MSDAvg*. The whole procedure can be represented by Eq. 3. Steps used by Algorithm-C to compute *MSD* and *MSDAvg* are as below:

- All geodetic coordinates of nodes and starting, ending and intermediary points of fiber segments belonging to fiber cables set of are inserted in KD-tree except those fiber segments and nodes which are in safe region.
- A set Y of geodetic coordinates of nodes and starting, ending and intermediary points of fiber segments of is constructed.
- A point-by-point iteration in Y (call it ƥ) to find a point of (suppose ƙ) which has already been inserted in KD-tree in the nearest neighbor using KNN search, and then the spatial distance between ƥ and ƙ is computed and store in set D.
- Return the least and average values as *MSD* and *MSDAvg* of pair () from set D.

Algorithm 1: DPMMSD

Input: An adjacency matrix **G** of the network, source node **s**, destination node **d**, 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**.

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

```
1   mmsd := -1, mmsdAvg := -1          i.e. initializing decision variables
2   Find K shortest lightpaths P and weights W from s to d 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-A given in appendix.
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 ($P_u, P_v$).
8               if mmsd ≤ MSD and mmsdAvg ≤ MSDAvg
9                   mmsd := MSD
10                  mmsdAvg := MSDAvg
11                  ConstrainedPair := ($P_u, P_v$)
12              end if
13          end if
14      end for
15  end for
```

In some cases, multiple link-disjoint pairs can have the same *MSD* value. In order to optimize the proposed algorithm, another decision variable as *MSDAvg* (represents the quantitative disjointness between the lightpaths) is computed which acts as a tiebreaker. Lines 8–12 decide the constrained pair of lightpaths with maximized MSD on the basis of *MSD* and *MSDAvg* values. Line 11 will provide the constrained pair as proposed in Eq. 3. For geo-calculations over a great-circle (i.e. finding distance, mid-point, intermediate point etc.) between two geodetic coordinates containing latitudes and longitudes, the formulae given in Calculate distance, bearing and more between Latitude, Longitude points (2017) have used. Certain fiber parts which are enclosed in the safe region are excluded in measuring the MSD.

3.2 Constrained disjoint lightpath pair with maximized minimum spatial distance problem

Provisioning of Constrained Disjoint Pair with Maximized Minimum Spatial Distance (CMMSD) Problem: Find a pair of link-disjoint lightpaths (P_u, P_v) such that the path

Table 1 Upper Bound Complexity Analysis

Algorithm	Complexity
Yen's Algorithm	$O(KN^3)$
DPMMSD	$O(K^2L^2S_{max}^2)$
CMMSD	$O(K^2L^2S_{max}^2)$

Table 2 Simulation Setup Parameters

Parameter Name	Value
Exclusion distance (δ)	10 km
Separation Distance (α)	50 km
Total No of Shortest Lightpath (K)	1000
T Distance (Threshold Value)	50 km

length W_u of the primary lightpath P_u is minimized while the minimum spatial distance (MSD) is constrained by a value α.

$$Constrained\ Pair \leftarrow \max_{(P_u,P_v)} \left\{ MSD_{(P_u,P_v)} < \alpha\forall \min_{(P_u,P_v)} \left\{W_u\right\} \right\} \tag{4}$$

Equation 4 has been extended from Eq. 3 by incorporating the α-constraint on *MSD* of subjected pair having minimum lengths. CMMSD algorithm is proposed in the context of the mentioned problem. The algorithm is divided into two parts, with the first part similar to the earlier DPMMSD algorithm referring to lines 1–2. Lines 3–17 find the desired disjoint pair of lightpaths with minimum lightpath length and the *MSD* constrained to **α** at lines 8–14 (whereas value mentioned in Tables 1, 2). Higher values of **α** represent large scale disasters whereas small value of **α** represents construction level failures.

Algorithm 2: CMMSD

Input: An adjacency matrix **G** of the network, source node **s**, destination node **d**, 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** and an *MSD* constraint value **α**.

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

```
$mmsdAvg$ := -1, $minWeight$ := ∞            i.e. initializing decision variables
Find K shortest lightpaths P and weights W from s to d using Yen's algorithm.
for u from 1 to K-1
    for v from u+1 to K
        matched := LinkMatching ($P_u, P_v$)  using Algorithm-A given in appendix.
        if pair ($P_u, P_v$) not matched     i.e. disjointed pair
            [MSD, MSDAvg] := Computing the minimum spatial distance and average of
            all minimum spatial distances between disjoint pair ($P_u, P_v$).
            if MSD < α and mmsdAvg ≤ MSDAvg
                if $minWeight > W_u$
                    $minWeight := W_u$
                    $mmsdAvg$ := MSDAvg
                    $ConstrainedPair := (P_u, P_v)$
                end if
            end if
        end if
    end for
end for
```

4 Proof-of-concept and complexity analysis

The proposed algorithms efficiently utilize two existing algorithms to provide faster and optimal solutions. One of these is Yen's algorithm which is a widely used algorithm to determine k-shortest lightpaths by deviating nodes until Kth shortest lightpath is discovered. Second one is Detection of Spatially-Close Fiber Segments (DSCFS) (Ashraf et al. 2018) which uses KD-tree processing to provide faster practical running time which is further improved when repeating-pairs and self-pairs are modestly discarded. In addition, the proposed algorithms integrate KNN search techniques in order to compute the MSD between lightpaths such that disjoint pair of lightpaths can be provisioned for any connection request. This kind of provisioning of primary lightpath along with the backup lightpath at maximum spatial distance improves the network survivability against wide-spread disastrous events. Moreover, taking the average of spatial distances as MSDAvg contributes towards optimization of solutions (i.e., helps to select the lightpaths distant apart as possible).

5 Simulation setup

When disjointness of primary and backup lightpaths is measured or constrained by spatial distance, then such type of routing is known as spatial disjoint lightpath routing. However, spatial distance for spatial-disjoint lightpaths is measured as zero when they share some link(s) or node(s). Finding maximally spatial-disjoint lightpaths pair may involve the following steps shown in Fig. 4.

The simulation parameters for the comparative study of proposed algorithms with other existing techniques are summarized in Table 2 where T Distance is taken from Wang et al. (2017).

5.1 Real-life network topologies

For simulation purposes, two real-life networks (*i*) European network and (*ii*) Internet2 US network have been considered as shown in Fig. 5. All nodes (network equipment) indicate some Point of Presence (PoPs) which is a location having geodesic coordinates in the form of latitude and longitude. Furthermore, optical fibers cannot be deployed in straight lines to connect nodes but in zig-zag manner due to terrestrial and government constrains, and have geographical information too i.e., contains geodesic coordinates. After selecting the study networks, set of coordinates for nodes as well as fiber links are collected which is later used for measuring spatial distance between nodes and links. European optical network topology contains 28 nodes and 41 edges as connecting links (Velasco et al. 2012). US network is the Internet2 network for advanced research collaboration network made up of 56 nodes and 66 links (Internet2 Network's Layer 1 Services 2018). Internet2 network eventually

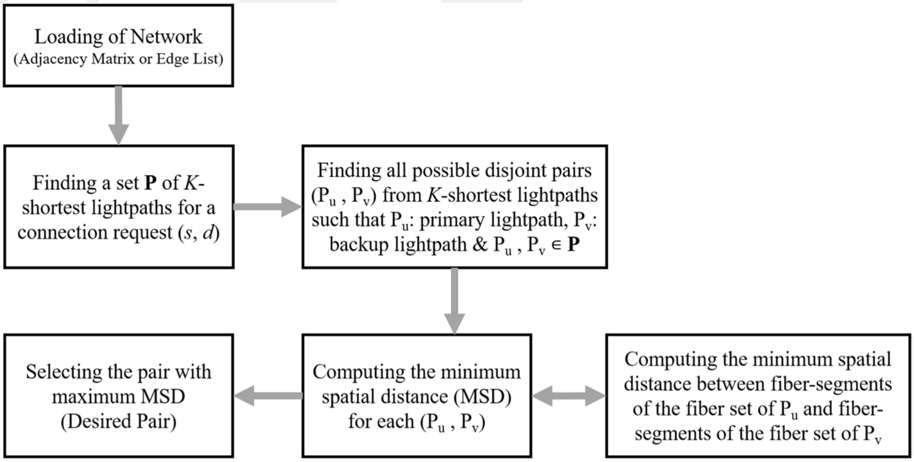
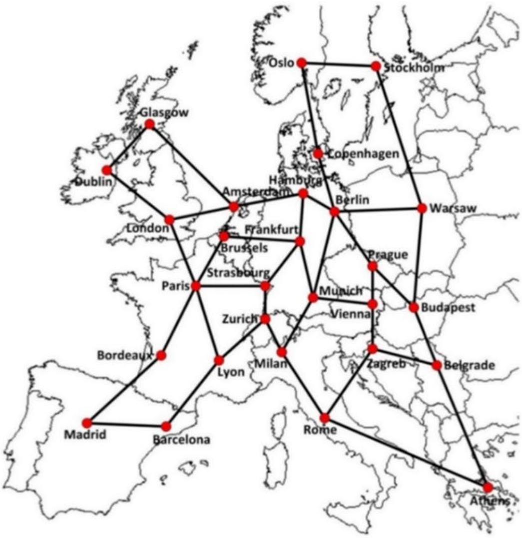
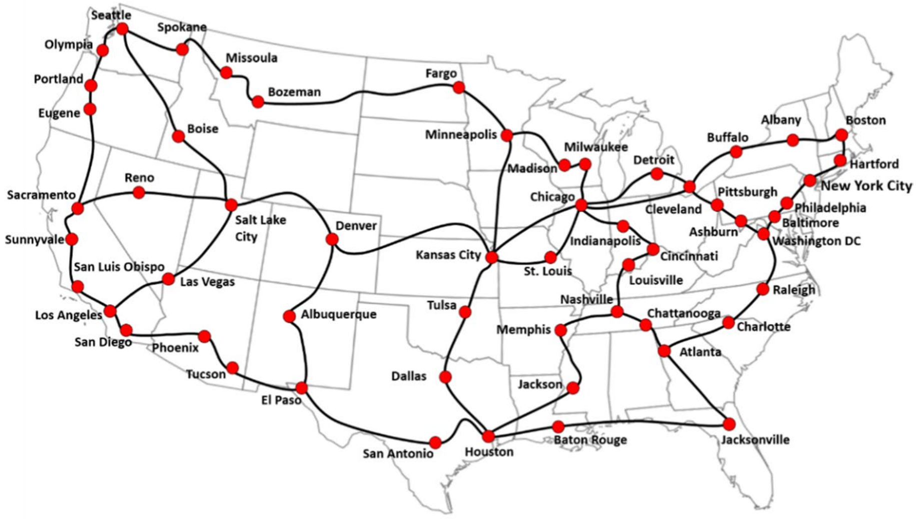


Fig. 4 Simulation setup for spatial-disjoint lightpaths



(a) European Network [25]



(b) US Network [26]

Fig. 5 Graphs of real-life networks topologies offers speeds of 1 terabit with more access points than any other research and development networks.

6 Simulation results and discussion

Simulated performance of both algorithms is evaluated using networks discussed in Sect. 5 and benchmarked with enhanced K-shortest path (EKSP) algorithm (Wang et al. 2017) given in "Appendix". EKSP provisions the disjoint pair of lightpath on the basis of minimum proximity factor (PF). PF is a ratio of number of under threshold nodes and the total nodes lightpath. The proposed algorithms consider the separation of nodes as well as the fiber links whereas EKSP considers only node separation. EKSP normalized the PF factor over the total nodes of lightpaths and provisions the pair with lowest PF. This implies that backup lightpath traversing most nodes would have least PF ratio which lakes to provide optimal backup lightpath.

All simulation results averaged over 5000 runs. Figures 6 and 7 depict the provisioning of link-disjoint pairs for the European and US networks respectively. Primary lightpaths are indicated as red colored lightpaths whereas blue colored lightpaths represent the backup lightpaths in the provisioned disjoint pair. From the Figs. 6 and 7, it is clear that DPMMSD and CMMSD determine the more optimal pairs as compared to EKSP.

It is already mentioned that source and destination nodes are supposed to be safe for a specified circular region of radius δ also known as excluding distance. Measurement of MSD between two lightpaths is taken, ignoring the safe region. For better understanding, refer to Fig. 8 which shows how MSD varies when radius of safe region (δ) changes at the starting or terminating nodes.

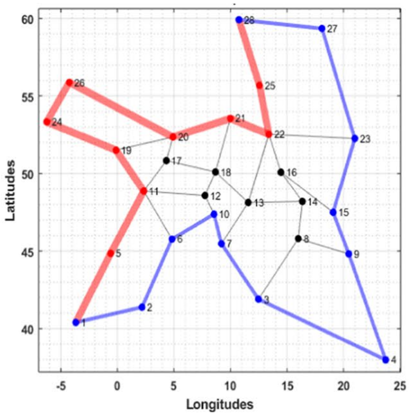
Hence increasing or decreasing δ can affect in measuring MSD which can be observed in Fig. 9. It has been observed that the value of MSD gradually increases as δ grows.

Figure 10 shows the declining impact of δ on the computing times for the proposed algorithms. By increasing the value of δ, more fiber segments will be enclosed within the safe region. While disregarding this region during the measurement of MSD, computation time will be reduced due to accounting a smaller number of fiber segments. It is worth mentioning that δ directly associates with the computation of MSD and its computation time, and could not relate to PF factor of EKSP. That is why, graph for PF against δ is not possible.

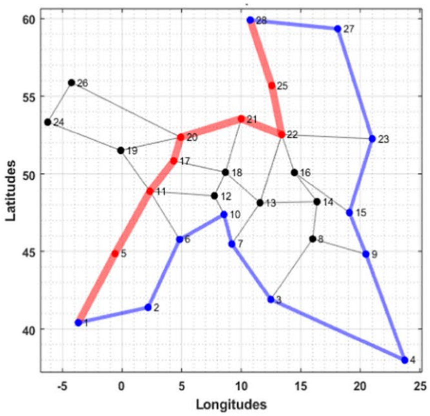
The effect of the number of shortest lightpaths (K) on computing disjoint pairs and corresponding computation time is shown in Figs. 9 and 10 for European and US networks respectively. From the Figs. 11a and 12a it is observed that proposed algorithms compute a smaller number of pairs as compared to EKSP as it involves self and repeating pairs in computation.

During simulation, it was observed that most of the simulation time was being consumed in finding and computing disjoint lightpath pairs and their least spatial distances. The K-Time graphs for selected networks using the proposed algorithms and EKSP are shown in Figs. 11b and 12b. The processing time rises exponentially and will be constant after finding all possible disjoint pairs of lightpaths as shown in Fig. 12b. When all possible disjoint pairs have been obtained and no pair can be computed further even by increasing the value of K, the computation time becomes constant. The K-Time graph shows that both of the proposed algorithms have almost the same computation time but lower than EKSP.

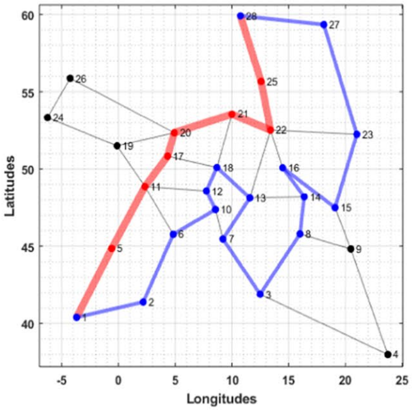
Fig. 6 Provisioning of disjoint pair of lightpaths in european network



(a) DPMMSD paired with MSD = 8.384 km, Wu = 4341.13 km, K = 1000 and δ = 10 km

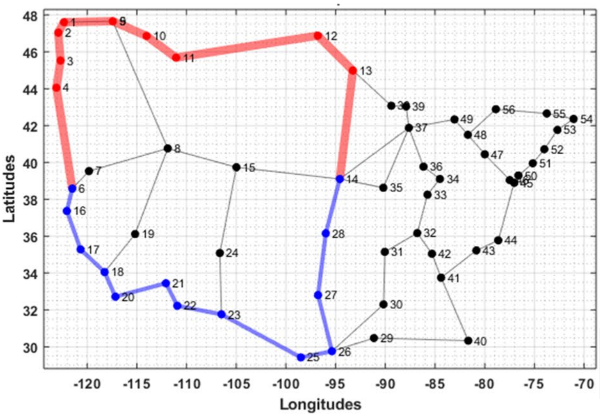


(b) CMMSD paired with MSD = 8.384 km, Wu = 2948.07 km, α = 50 km, K = 1000 and δ = 10 km

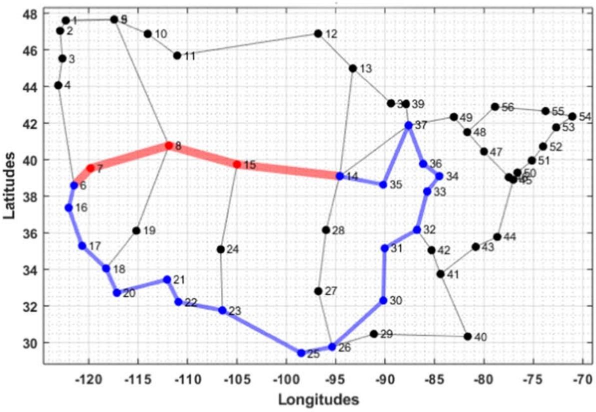


(c) EKSP pair with PF = 0.143 for K = 1000

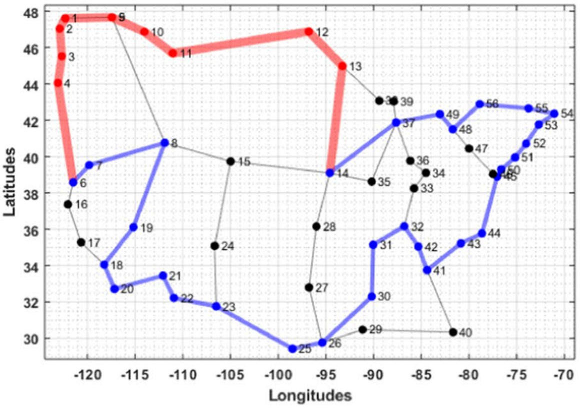
Fig. 7 Provisioning of disjoint pair of lightpaths in US network



(a) DPMMSD paired with MSD = 19.25 km, Wu = 5008.37 km, K = 1000 and δ = 10 km



(b) CMMSD paired with MSD = 19.13 km, Wu = 2359.4 km, α = 50 km, K = 1000 and δ = 10 km



(c) EKSP paired with PF = 0.72 for K = 1000

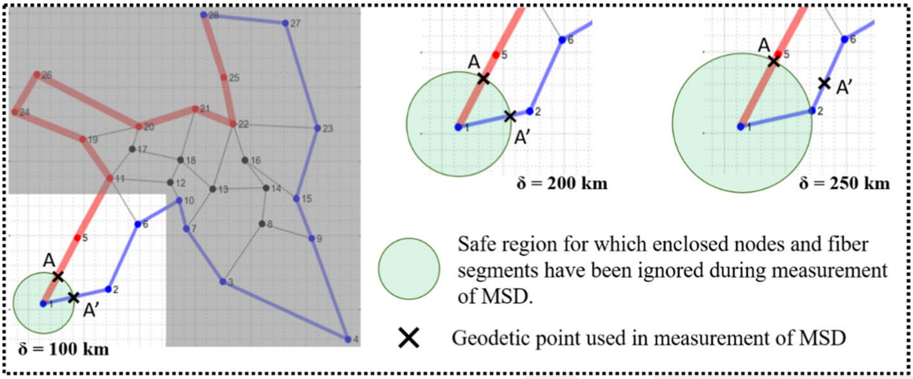
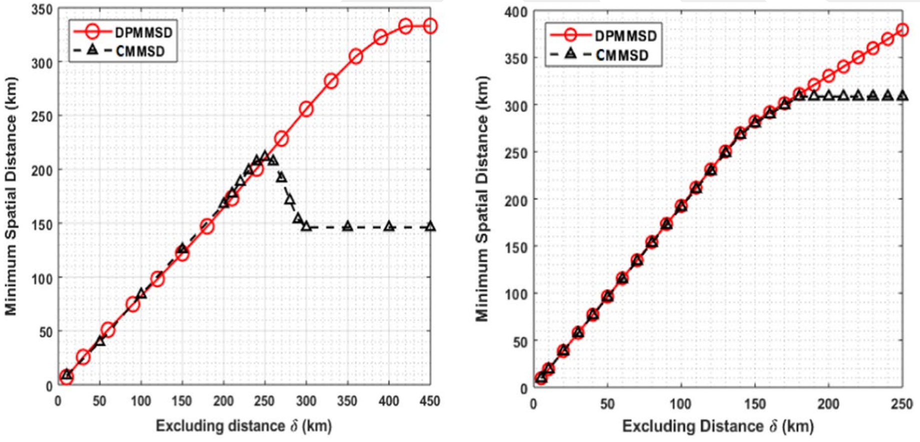


Fig. 8 Effect of δ on measurement of MSD



European Network US Network

Fig. 9 Exclusion distance (δ) vs. MSD

7 Conclusions

This research proposes two disaster aware routing algorithms for computing a backup lightpath between two network nodes. First algorithm finds a pair of lightpaths with a maximum value of MSD, while second algorithm finds a pair of lightpaths with primary lightpath of minimized weight but constraint by MSD. Through simulation of DPMMSD, CMMSD and the benchmark EKSP enables the evaluation and comparison of the performance. EKSP computes more pairs hence takes more computing time

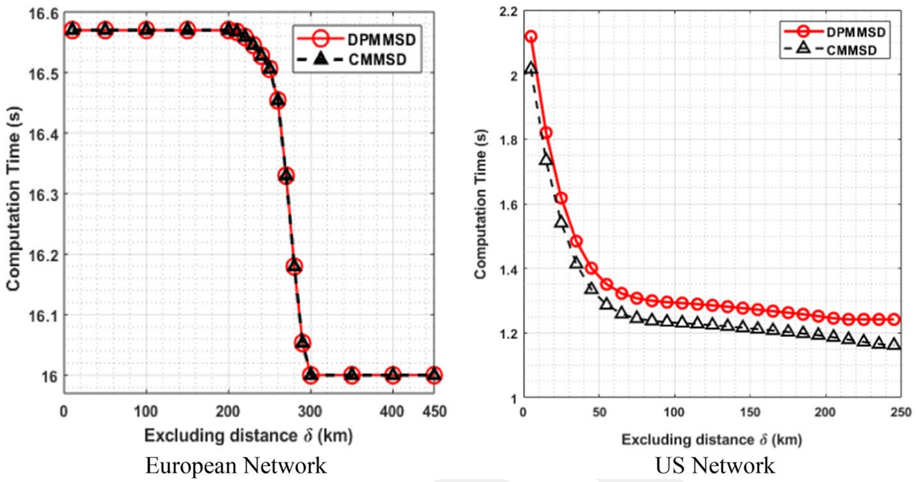
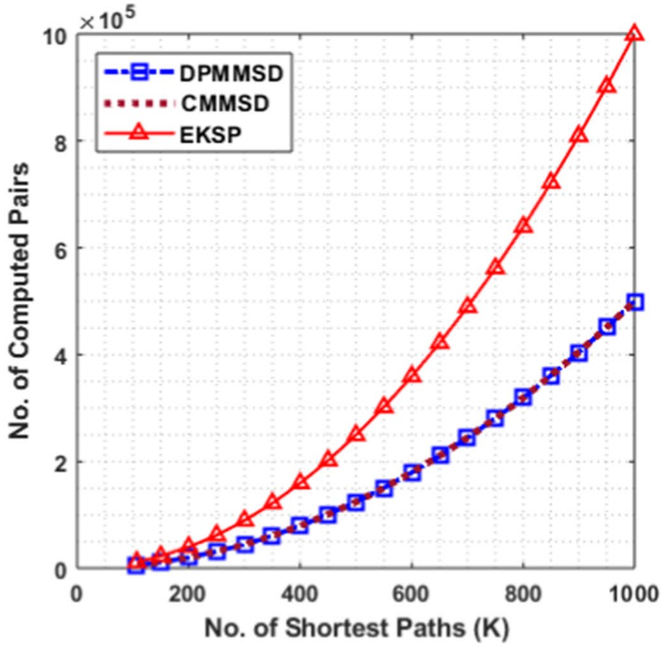
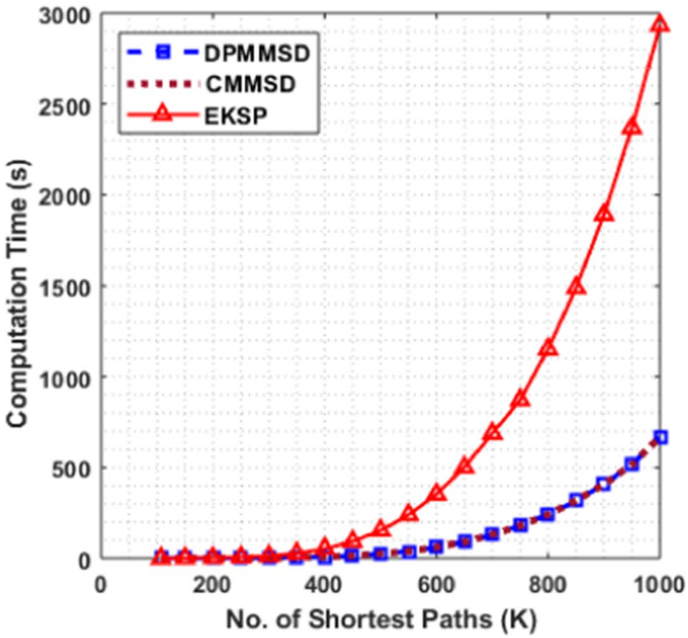


Fig. 10 Exclusion distance (δ) vs. computation time

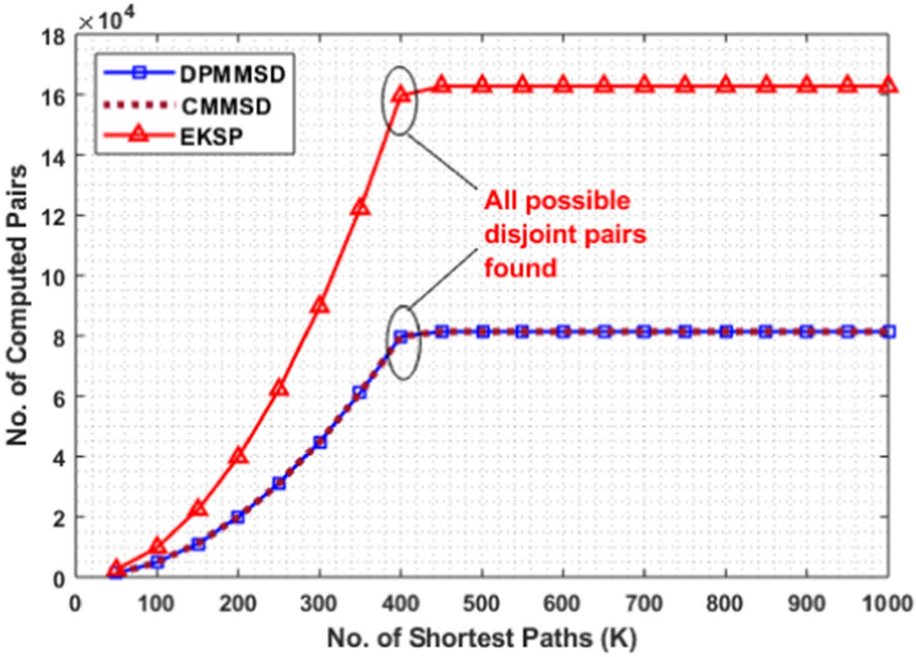


(a) No. of Shortest Paths vs Disjoint Pairs

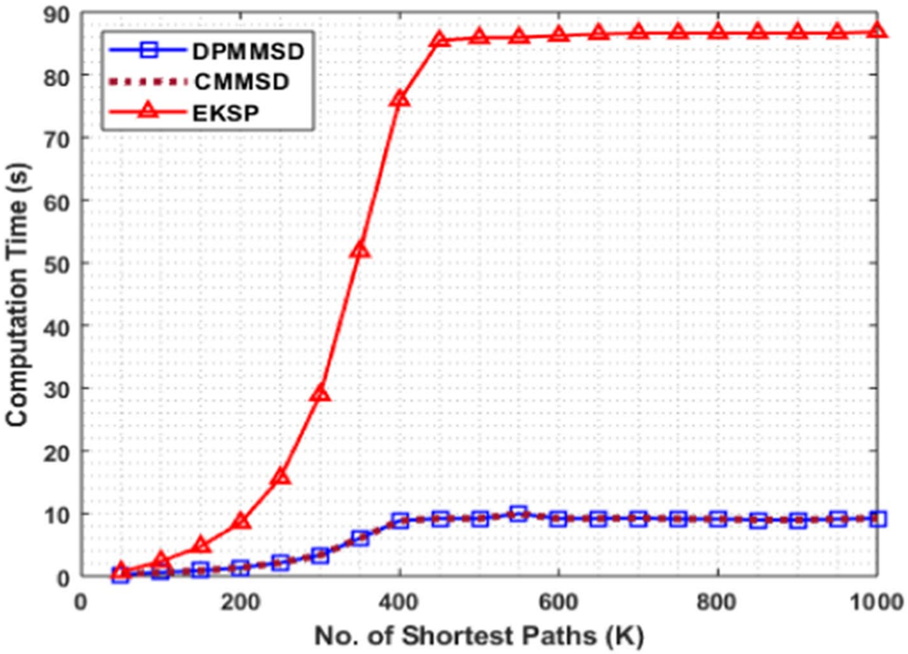


(b) No. of Shortest Paths vs Computation Time

Fig. 11 Effect of K for δ = 10 km and α = 50 km in European network



(a) No. of Shortest Paths vs Disjoint Pairs



(b) No. of Shortest Paths vs Computation Time

Fig. 12 Effect of K for δ = 10 km and α = 50 km in US network whereas DPMMSD and CMMSD modestly discard the computation of self and repeating pairs, enabling quick computations.

Appendix

Algorithm-A: *Yen's K-Shortest Path Algorithm* [27]

Input: An adjacency matrix ***G*** of the network, source node ***s***, destination node ***d*** and the desired number of shortest paths ***K***.

Output: Sets of paths $P = \{P_1, P_2, P_3, \cdots, P_k\}$ and weights $W = \{W_1, W_2, W_3, \cdots, W_k\}$.

```
$[P_1, W_1]$ := Shortest path and weight from s to d using Dijkstra Algorithm
tempG := G
for $k$ from 2 to $K$
    for $i$ from 1 to size ($P_{k-1}$) - 1
        currentNode := $P_{k-1}(i)$
        $[R_i, W_{si}]$ := The sub-path and sub-weight from s to currentNode using Dijkstra
        for $j$ from 1 to $k$ - 1
            $[R_j, W_{sj}]$ := The sub-path and sub-weight from s to $P_j$ using Dijkstra Algorithm
            if $R_i == R_j$
                nextNode := $P_j(i + 1)$
                tempG (currentNode, nextNode) := ∞
                Make the currentNode unreachable
            end if
        end for
        $[S_i, W_{ci}]$ := Shortest lightpath and weight from currentNode to d using Dijkstra
        $[X_i, W_i] := [R_i + S_i, W_{si} + W_{ci}]$
    end for
    $[P_k, W_k]$ := Shortest path amongst all paths in $X$
    tempG := G
end for
```

Algorithm-B: *Enhanced K-Shortest Path (EKSP) Algorithm* [40]

Input: An adjacency matrix G of the network, source node ***s***, destination node ***d***, desired number of shortest paths K and $T_{distance}$ distance threshold below which nodes are counted as being geographically close.

Output: A pair of link-disjoint lightpaths with smallest proximity factor (PF).

```
$smallestPF := \infty$, $ConstrainedPair := \emptyset$
Find $K$ shortest lightpaths $\mathbf{P}$ and weights $\mathbf{W}$ from $s$ to $d$ using Yen's algorithm (Algorithm-A).
for u from 1 to K
    for v from 1 to K
        $[PF, (P_u, P_v)]$ := Computing the proximity factor of pair $(P_u, P_v)$ using Algorithm-C.
        if $PF < smallestPF$
            $smallestPF := PF$
            $ConstrainedPair := (P_u, P_v)$
        end if
    end for
end for
return $ConstrainedPair$
```

Algorithm-C: *Calculating Proximity Factor (PF) between lightpaths* [40]

Input: $T_{distance}$ distance threshold below which nodes are counted as being geographically close. A pair of lightpaths($\mathrm{P_u}, \mathrm{P_v}$) such that $\mathrm{P_u} := \{s, R_{m1}, R_{m2}, \cdots, R_{mr}, d\}$ and $\mathrm{P_v} := \{s, R_{n1}, R_{n2}, \cdots, R_{nk}, d\}$ where R_{mi} and R_{ni} are the i_{th} nodes along the lightpaths.

Output: The proximity factor (PF) between lightpaths $\mathrm{P_u}$ and $\mathrm{P_v}$.

```
$PF := 0$
for each $R_{mi}$ in lightpath $\mathrm{P_u}$
    for each $R_{ni}$ in lightpath $\mathrm{P_v}$
        if $D(R_{mi}, R_{ni}) < T_{distance}$
            $PF := PF + 1$
        end if
    end for
end for
$PF := PF / \mathrm{Hops}(\mathrm{P_u})$
return $PF$
```

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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