Disaster-Aware Submarine Fiber-Optic Cable Deployment

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Abstract

Network survivability is an important element in telecommunication network design nowadays because of the social and economic reliance on the Internet and the significant cost associated with service interruption. Moreover, the fact that submarine fiber-optic cables are susceptible to man-made or natural disasters, such as earthquakes, is well recognized. A disaster-resilient submarine cable deployment can save cost incurred by network operators such as the capacity loss cost, the cruising cost and the repair cost of the damaged cables, in order to restore network service when a cable break is prompted by a disaster occurrence. In this work, we investigate disaster-aware submarine cable deployment problem. While selecting a path for the cables, our approach aims to minimize the total expected loss cost, considering that submarine fiber-optic cables may break because of natural disasters, subject to deployment budget, path uniqueness, regular protection, elliptic shape, and linearization constraints. In our approach, we assume disaster-unrelated failures are handled by providing a backup cable along with primary cable. We consider a scenario with two nodes located on two different lands separated by a water body (sea/ocean). We then consider an elliptic cable shape to formulate the problem, which can be extended to other cable shapes, subject to avoiding deploying cable in disaster zones. We provide an Integer Linear Programming formulation for the problem. Finally, we present illustrative numerical examples that show the potential benefit of our approach as well as conclusion and future work.

Keywords—Submarine fiber-optic cable, undersea disasters, disaster resiliency, optimization.

I. INTRODUCTION

The world has undergone a communication revolution from 1988 when the first transoceanic fiber-optic cable was laid which connected Britain, United States of America, and France. This was a result of tremendous technology push and market pull. Now network connectivity heavily relies on fiber-optic submarine cables, which have become more essential in our lives, given our social and economic reliance on the Internet. Unfortunately, this strong reliance is mainly recognized and appreciated when there are cable failures. Statistics show that about 70% of total submarine fiber-optic cable faults are a result of external aggressions mainly associated with human activities (e.g., shipping, fishing, and anchorage). Moreover, 75% of all submarine fiber-optic cable faults occur in water depths shallower than 200 m, because of fishing and shipping activities [1]. These failures can be reduced by providing additional shielding at a minimum cost by employing approaches like Zhang *et al.* [2] present. Despite the fact that failures caused by natural disasters are less than 10% of all failures (occurred both in deep and shallow water), when focusing on deep-water cables, at least 31% of submarine cable failures are prompted by natural disasters [1]. Based on these statistics, efforts to address the problem of submarine cable failure have been focusing on eradicating faults resulting from human activities, while paying little attention to the remaining causes. These causes constitute 30% of cable breaks in deep water, simply because we are often guided by heuristics and rules of thumb to address disaster planning. Berger *et al.* [3] point out some useful lessons to guide us in making decision about disaster planning by distinguishing losses caused by natural disasters from occurrences of natural disasters. Despite the fact that natural disasters constitute less than 10% of total external aggressions, its consequences to submarine cable industry is significant, hence, paying little attention to it, is a myopic disaster planning. Berger *et al.* [3] stipulate two components that lead to losses from a natural disaster: (1) whether or not a natural disaster occurs and (2) the size of the loss as a result of occurrence of a natural disaster. Consequently, loss distribution evaluation must involve two components: occurrence and magnitude. Additionally, the distinction between these two components is critical for optimal decision making [3].

Below, we provide some facts and figures on the effects of submarine fiber-optic cable disruptions due to disasters and we can see that disaster-aware submarine cable deployment considering the loss in case of a disaster is a must to reduce (or even eliminate) such damages.

In 2006, the Pingtung (aka Hengchun) earthquake in Taiwan of a magnitude 7.0 earthquake prompted mud flows and submarine landslides that travelled over 246 km at a depth greater than 4 km, causing 22 submarine fiber-optic cables break [4]. Eventually, telephone systems, data and Internet traffic were extensively disrupted in China, Taiwan, Hong Kong, Macao, and other countries, and the process of repairing the affected cables took seven weeks.

The authors of [1] considered different natural disasters occurring in different regions together with their effects to submarine fiber-optic cables viz.: (i) The 2009 Typhoon Morakot in Taiwan prompted sediment laden flows that broke at least nine submarine fiber-optic cables. (ii) In 2003, the Boumerdes earthquake of magnitude 6.8 earthquake in Algeria

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triggered landslides and turbidity currents which damaged six submarine fiber-optic cables, hence disrupted all submarine fiber-optic networks found in the Mediterranean region. (iii) Following the Tsunami generated by the Andaman-Sumatra earthquake in 2004, land-based telecommunications networks were damaged in coastal Malaysia and South Africa. We learn from [5] that, The Great East Japan Earthquake of magnitude 9.0 earthquake off the coast of Japan that occurred on March 11, 2011, is the fourth strongest earthquake ever occurred in the world. This stringently affected telecommunication infrastructure, as the author of [5] reveals that, considering Nippon Telegraph and Telephone Corporation's (NTT) facilities, 2700 km of cables were swept away, 1.5 million circuits for fixed lines as well as 4900 mobile base stations were severely damaged. The list of natural catastrophes that have occurred, and their consequences to human lives, as well as submarine fiber-optic cable infrastructures, is endless. Submarine fiber-optic cable break caused by natural disasters has significant economic loss as a research conducted in 2005 by the Swiss Federal Institute of Technology (ETH) Zurich found that if there is an Internet blackout in the entire country of Switzerland that last for one week, the country will experience a monetary loss of over 1.2% of its GDP [6].

A survey on existing research publications associated with disaster survivability in optical networks is provided in [7], where the authors classify disasters into three groups viz: predictable, non-predictable and intentional attack, based on their characteristics and impacts on networks. Additionally, in [7] disaster modelling approaches are classified into two categories namely deterministic models and probabilistic models. Deterministic model assumes that a network equipment such as link or node fails with probability 1 if it is located within a disaster zone and 0 otherwise. In contrast, in probabilistic model a network equipment fails with a certain probability, which depends on factors such as its distance from the disaster epicenter, dimension of the equipment, specifications, etc. [7]. Our approach uses probabilistic model because there are many factors that may affect cable response to earthquake and therefore a probabilistic model is more appropriate and more realistic than a deterministic approach.

There are some recent work that focus on disaster-resilient network design and traffic engineering, but mostly they focus on impacts of disasters to terrestrial networks and cables buried under ground as in [2], [8-12]. Cao *et al.* [13] investigate a disaster-resilient network design particularly in submarine environment. Authors' approach focuses on network survivability and cable shapes aspects in addressing the cost of network deployment without giving detailed results as to what monetary loss is associated with a given disaster.

In order to design a robust network against earthquake, Saito [11] proposes spatial network design rules which include three components: (1) a shorter zigzag route which can reduce the probability of networks falling in disaster zones, (2) additive performance metric, where repair cost and network's shape are independent if the length of the route is fixed and (3) probability that all nodes intersect the disaster area is not reduced by additional of routes within a ring network. Saito [12] presents geometric model of a physical network affected by a disaster, which can be used in evaluating performance metrics of a network such as network connectivity. Unlike [11] and [12] that consider survivability metrics such as network connectivity, we consider costs incurred by submarine fiber-optic cable owners, shape of the cable, topography of submarine environment, as well as the probability that a natural disaster occurs considering cable break is prompted by a natural disaster, particularly in submarine environments. To the best of our knowledge, this study addresses a unique concept from the existing research publication associated with disaster survivability of submarine fiber-optic cables.

We study a disaster-aware submarine fiber-optic cable deployment by using a probabilistic model. Our approach investigates the cost incurred by submarine fiber-optic cable owners to restore network service to a normal condition when submarine fiber-optic cables breaks as a result of natural disasters based on the probability of natural disaster occurrences as well as the probability of cable breaks. Thereafter, we evaluate the total cost that is a sum of cruising cost (cost of repair ship to arrive at a failure point from closest station), repairing cost, and penalty due to bandwidth loss. In a nutshell, our approach minimizes losses incurred by submarine fiber-optic cable owner following a cable break due to a disaster occurrence by deploying a disaster-aware submarine fiber-optic cable deployment significantly with a slight increase in deployment cost.

II. Problem Description and Assumptions

Consider two continents or islands (or land masses) to be connected by submarine fiber-optic cables. The two land masses can be connected by one or more fiber-optic cables. When the two landmasses are connected by one submarine fiber-optic cable, a connection is not protected, hence, a connection failure will be experienced if cable break occurs. Ramamurthy and Mukherjee [14] studied protection in WDM networks using two paradigms viz; link protection/restoration and path protection. Spilios *et al.* [15] studied metrics for measuring the robustness of undersea cable infrastructure wherein resiliency is one of them. Considering findings presented in [14] and [15], our study provides a protected connection between the two landmasses by connecting them using by two submarine fiber-optic cables[1] denoted by $i = \{1, 2\}$ such that it is equal to 1 for primary cable and 2 for backup cable. Whereby, the water body separating the two continents is susceptible to a number of possible natural disasters. In particular, we consider the problem of the best way to connect the two nodes located on the beaches of the two continents (islands) as shown in Figure 1. The assumption that the two nodes are located on the beaches is made for simplicity and for ease of exposition. Allowing the nodes to be located inland will require considerations of different costs for laying and repairing cables in the sea and inland, which introduces additional complexity in to the problem. However, our solutions for the simpler case can be extended to the case where the nodes are located inland. Various topologies can be employed to provide

[1] We can easily generalize our approach for any number of cables, but for simplicity (and as in typical practice), we keep the number of paths to two.

connection between these two nodes, e.g., rectangular, circle/ring, triangular, etc.

Cao *et al.* [13] present topology optimization of undersea cables in which various cable shapes are considered including rhombus, rectangular, and a rectangle with round corners. Eventually, [13] focused on a rectangular topology in their study, aiming at decreasing the probability of simultaneous cable breaks considering natural disaster occurrences. In our approach, we focus on elliptic cable shape, which is more cost effective in terms of deployment cost.

Unfortunately, there is no simple closed-form formula for calculating perimeter of an ellipse, as there is for a circle, a rectangle, etc. Thus, even though there are simple equations, yet there is no simple and exact equation. The list of these equations includes; First Approximation, Second Approximation (Ramanujan), Infinite series 1, Infinite series 2, etc. Some studies (e.g., [16]) on the existing equations and their findings proved that Second Approximation by Ramanujan performs better than others. Hence, in this study, we apply this equation. The Second Approximation states that the perimeter of an ellipse is given by:

$$P = \pi\left(a + b\right)\times\left(1 + \frac{3h}{10 + \sqrt{4 - 3h}}\right), \tag{1}$$

where a is the major axis, b is the minor axis, and h is defined as $h = \frac{(a-b)^2}{(a+b)^2}$ that ranges from 0 for circles ($b = a$) to 1 for the degenerate (b = 0). Observe that, for submarine fiber-optic cables, the distance between two nodes is very large (about 5,000 km to 30,000 km), so $a >> b$, which approximates h to 1. Thus, equation (1) can be reduced to:

$$P = \pi\left(a + b\right)\left(14 / 11\right) \tag{2}$$

Therefore, given the cost of deployment per unit kilometer (C_d) and Eq. (2), the cost of deployment of a cable (that is half of the ellipse) is:

$$C = C_d \times \pi\left(a + b\right)\left(7 / 11\right) \tag{3}$$

Furthermore, deployment cost increases when the values of the major and minor axes of the ellipse increase. However, since major axis is a given parameter in our problem, we can optimize the minor axis such that expected total cost is minimized, subject to deployment budget constraint. The expected cost includes expected (i.e., probabilistic) cost incurred by the network operator to restore network connections due to a cable break. Clearly, the lower the probability of cable break, the lower is this expected repair cost.

We consider a set of candidate cable paths as shown in Figure 1. Let Ω be a set of possible disasters wherein each disaster is assumed to be a circular disk, characterized by location, radius and strength. The epicenter of a disaster is a typically located near earthquake faults. For each $n \in \Omega$, let $P_{j,i}^{n}$ be the probability that, if disaster n occurs and if candidate path j is selected for cable i, cable breaks. This probability depends on the distance of the cable from the disaster epicenter and follows a certain given function which decays as the distance of the cable from the epicenter increases [17] (e.g., following a Normal distribution).

Additionally, when a cable passes through a disaster zone and break as a result of that disaster, then a set of costs will be incurred by the network operator to restore the service; namely, cost of repair (C_r per km), cost of cruising to the cable-break location to do technical repair (C_t per km), and penalty (C_p per unit of bandwidth lost) due to breach of service level agreement (SLA). Effects of the disaster will damage length $L_{i,j}^{a,n}$ of cable i, if candidate path j is selected, passing through disaster n. We assume that one of the repair ships at the closest station will travel length $L_{i,j}^{u,n}$ to visit affected part for reparation activity. These lengths are shown in Figure 1.

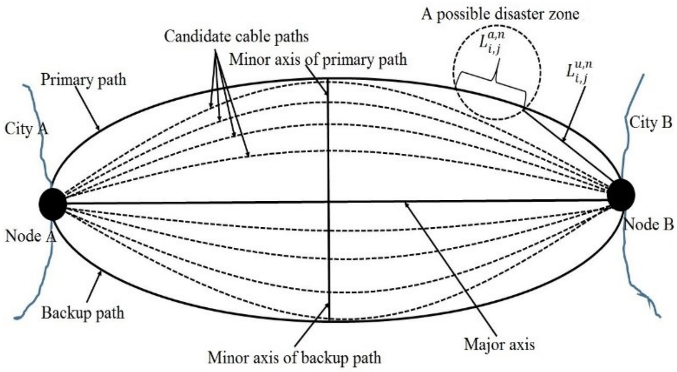

Fig. 1 Elliptic shape candidate cable paths connecting two nodes located on two beaches.

III. Problem Formulation

Based on the above-defined parameters, we develop an Integer Linear Programming (ILP) formulation that considers physical location of disasters, radii of disasters, physical location of submarine fiber-optic cable, shape of the cable, and their distance from disasters' epicenters. By exploiting this information, we obtain numerical values of the expected cost to be incurred by the network operator if a cable break due to a natural disaster occurrences. This cost is a summation of expected repair cost, expected cruising cost, and expected capacity loss penalty. We investigate a disaster-aware submarine fiber-optic cable deployment approach wherein a path is selected from the candidate paths based on these metrics in order to minimize loss incurred by the network operators subject to deployment budget constraint, path uniqueness constraint, regular protection constraint, elliptic shape constraint, and constraint due to linearization.

Symbol notation:

M = a set of minor axes for each candidate cable path, V_j is the length of minor axis for j^{th} candidate cable path.

Ω = a set of possible disasters characterized by their location, radius and strength.

$B_{i,j}$ = a binary variable, such that;

$$B_{i,j} = \begin{cases} 1, \text{ if } j\text{th candidate cable path is selected for cable } i \\ 0, \text{ Otherwise} \end{cases}$$

Then, given M and Ω, the repair cost (RC) of cable i with respect to damage caused by disaster $n \in \Omega$ can be defined as:

$$\text{RC} = \sum_{n \in \Omega} \sum_{i \in \{1,2\}} \sum_{j \in M} C_r \times L_{i,j}^{a,n} \times B_{i,j} \tag{4}$$

Additionally, we consider during reparation activity a cruising ship will cruise twice a distance $L_{i,j}^{u,n} + L_{i,j}^{a,n}$. Thus, we evaluate cruising cost (CC) to repair cable i after disaster n as:

$$\text{CC} = \sum_{n \in \Omega} \sum_{i \in \{1,2\}} \sum_{j \in M} 2 \times C_t \times B_{i,j} \times \left(L_{i,j}^{u,n} + L_{i,j}^{a,n}\right) \tag{5}$$

Moreover, given the total capacity provided by the two cables (N) and a pre-computed value ($X_{n,i}^{j}$) such that:

$$X_{n,i}^{j} = \begin{cases} 1, \text{ if cable } i \text{ is deployed on } jth \text{ candidate cable path} \\ \quad \text{and passes through disaster zone } n \\ 0, \text{ otherwise.} \end{cases}$$

Thus, penalty due to capacity loss (CLP) by disaster n can be defined as:

$$\text{CLP} = \sum_{n \in \Omega} \sum_{k \in M} \sum_{j \in M} \boldsymbol{C_p} \times N \times X_{n,1}^{j} \times B_{1,j} \times X_{n,2}^{k} \times B_{2,k} \tag{6}$$

We assume that the penalty is due when both primary and backup cables are damaged for capacity loss. Observe that, in Eq. (6), the multiplication of two binary variables makes our formulation non-linear. To make it linear, we provide an auxiliary binary variable which is equal to logic AND operation of these two binary variables, i.e., if they are both 1, it is equal to 1, otherwise it is 0. Thus, it does not induce any error.

Let $D_{j,k}$ be an auxiliary binary variable such that:

$$D_{j,k} = \begin{cases} 1, \text{ if } B_{1,j} \times B_{2,k} = 1 \\ 0, \text{ Otherwise} \end{cases}$$

Subject to:

$D_{j,k} \le B_{1,j}$,
$D_{j,k} \le B_{2,k}$, and
$D_{j,k} \ge B_{1,j} + B_{2,k} - 1$.

Hence, (6) can be rewritten as:

$$\text{CPL} = \sum_{n \in \Omega} \sum_{k \in M} \sum_{j \in M} C_p \times N \times X_{n,1}^{j} \times X_{n,2}^{k} \times D_{j,k} \tag{7}$$

Then, our objective function is as follows.

Minimize the expected total loss cost (expected repair cost + expected cruising cost + expected capacity-loss penalty), considering all possible disasters.

$$\text{Min} \underbrace{\sum_{n \in \Omega} \left(\sum_{i \in \{1,2\}} \sum_{j \in M} C_r \times L_{i,j}^{a,n} \times B_{i,j} \right) \times P_{j,i}^{n}}_{\textit{Expected repair cost}}$$
$$+ \underbrace{\sum_{n \in \Omega} \left(\sum_{i \in \{1,2\}} \sum_{j \in M} 2 \times C_t \times \left(L_{i,j}^{u,n} + L_{i,j}^{a,n}\right) \right) \times P_{j,i}^{n}}_{\textit{Expected cruising cost}}$$
$$+ \underbrace{\sum_{n \in \Omega} \left(\sum_{k \in M} \sum_{j \in M} C_p \times N \times X_{n,1}^{j} \times D_{j,k} \times X_{n,2}^{k} \right) \times P_{j,1}^{n} P_{k,2}^{n}}_{\textit{Expected Capacity loss cost}} \tag{8}$$

Subject to:

a. Deployment budget constraint.
Deployment cost must not exceed budget (γ):

$$\sum_{i \in \{1,2\}} \sum_{j \in M} \left(\pi \times C_d \times \left(a + V_j\right) \times B_{i,j}\right) \le \gamma. \tag{9}$$

b. Path uniqueness constraint.
Only one candidate path is selected for each cable:

$$\sum_{j \in M} B_{i,j} = 1 \qquad \forall i;\ i \in \{1,2\}. \tag{10}$$

c. Regular protection constraint.

Primary and backup cables must be separated by at least some distance to avoid losing both cables by a regular failure (e.g., cable cut due to anchoring):

$$\sum_{i \in \{1,2\}} \sum_{j \in M} B_{i,j} \times V_j \ge S. \tag{11}$$

d. Elliptic shape constraint.
In any case, the minor axis should not be zero (i.e., the major axis should not be one of the candidate paths):

$$\sum_{j \in M} \left(V_j \times B_{i,j}\right) \ge 0 \qquad \forall i;\ i \ge 1. \tag{12}$$

e. Constraints due to linearization;

$$D_{j,k} \le B_{1,j} \qquad \forall j \in M, j \ge 1, \forall k \in M, k \ge 1, \tag{13}$$

$$D_{j,k} \le B_{2,k} \qquad \forall j \in M, j \ge 1, \forall k \in M, k \ge 1, \tag{14}$$

$$D_{j,k} \ge B_{1,j} + B_{2,k} - 1 \qquad \forall j \in M, j \ge 1, \forall k \in M, k \ge 1. \tag{15}$$

Since, for each cable i and each candidate path j, we have binary variable $B_{i,j}$ and for each pair of candidate cable path we have auxiliary binary variable $D_{j,k}$, the number of variables in the ILP is $I \times J + J^2$, where I is the number of cables (e.g., 2 in our examples) and J is the number of candidate path for each cable. Similarly, the number of constraints is $3(I + J^2) + 1$.

IV. Illustrative Numerical Examples

We present numerical examples to evaluate our approach for different dimension of major axis, different radius sizes of disasters, different interval of minor axes between consequent candidate cable paths, and deployment budget. All parameters used in our simulation are determined by information from public sources such as [18] and [19]. These parameters are normalized as follows; deployment cost per km is normalized to 1, cruising cost per km is normalized to 0.4, repair cost per km is normalized to 0.6. Moreover, minimum cable separation distance (S) required to avoid regular failures is 10 km, penalty due to capacity loss is 100 per Tbps and the total capacity of the two cables is 54 Tbps, i.e., 27 Tbps for each.

The author of [20] performed a study aiming at investigating the minimum distance at which an alternate facility should be placed in which different categories of disasters such as hurricane, storm and snow, earthquake, volcano, tsunami, terrorism, etc. are considered. Records from this study show that hurricane recorded maximum distance of 105 miles whereas storm and snow, earthquake, volcano, and tsunami recorded 68, 60, 75, and 51 miles of minimum distance, respectively.

Based on this study, we assume the maximum value of minor axis for each cable is 110 km, because by considering results from [20] this distance is sufficient to achieve a solution of higher precision. Additionally, if the selected intervals between cables are 1 km, 2 km, 5 km, 10 km, or 20 km, then we have 120, 60, 24, 12 or 6 potential solution paths, respectively. Note that the two paths will converge towards each other at the nodes, so it is not a factor that can be avoided. Besides, in this study we focus on the deep-water cable failures.

All our simulations have been rerun 50 times for each parameter set values and the results shown in Figure 2, Figure 3 and Figure 4 are average of the results obtained. We compared our approach with a disaster-unaware approach, which only considers regular failures. We report the results in terms of reduction in expected cost (expected cost of repair, cost of cruising to the cable break location, and penalty due to bandwidth loss) and increase in deployment cost compared to disaster-unaware approach.

A. Major Axis

Figure 2 shows the results for different major axis length values. Here we consider five disaster zones with radius of 30 km and a second set with ten disaster zones with radius of 50 km. The results show that our approach reduces expected cost significantly (between 75% and 97% depending on major axis) for a slight increase in deployment cost (around 18.1 %).

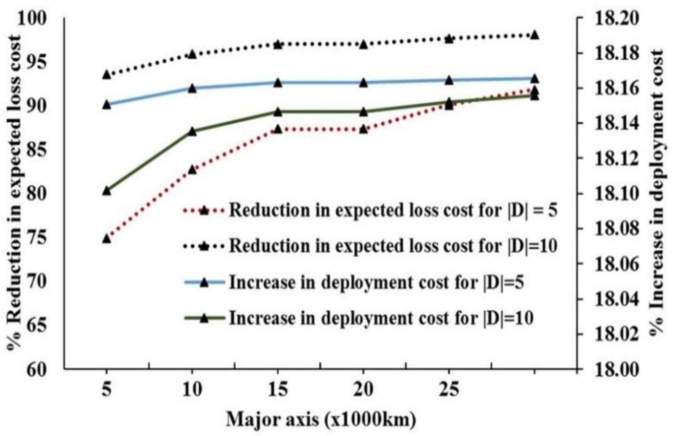

Fig. 2 Reduction in expected cost and increase in deployment cost for different major axis length values.

The effect of our approach is more evident when the distances between the land parts are larger. Thus, our approach is suitable in long-haul networks such as submarine fiber-optic networks because of their long-range coverage which spans over 30,000 km between two nodes. Moreover, when there are more possible disasters, our approach may reduce the expected cost more, a practical advantage.

B. Radius Size

We conducted numerical examples using five disaster zones of variable radius, followed by another example which involved ten disaster zones, likewise, with variable size. Here, the major axis is 15,000 km. The results are shown in Figure 3. We learn that, the ability of our approach to reduce expected loss cost is limited by both the size of the disaster zones and the number of disaster zones. This is due to the fact that, under such circumstances it becomes more difficult to avoid passing through disaster zones. However, our approach eventually chooses the no-risk or low-risk paths for primary and backup cables, so that it can still reduce the expected loss cost around 41% for large disaster zones.

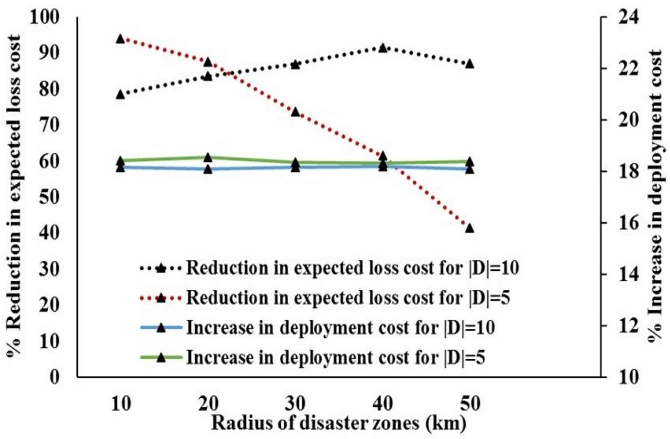

Fig. 3 Radius size vs. costs.

C. Interval between Minor Axes

Figure 4 shows the results for different values of candidate paths, when we select them with minor axes 1 km, 2 km, 5 km, 10 km, or 20 km apart from each other.

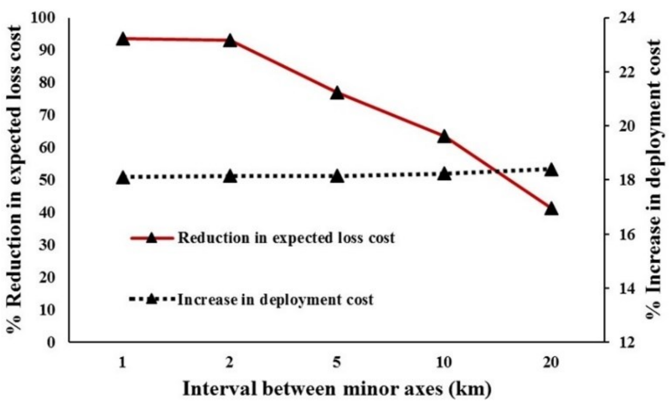

Fig. 4 Reduction in expected cost and increase in deployment cost for different interval between minor axes.

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The results show that we can improve the quality of the solution when the intervals between candidate paths are smaller at the expense of execution time of the optimization, as indicated by Table I. Because, when we have more candidate paths, it will increase the size of the problem as well as the number of potential solutions.

The execution times are shown in Table I. When the interval is 1 km (which means that there are 120 candidate paths for each cable), it requires 1000 milliseconds to run vs. when the interval is 20 km (which means there are six candidate paths for each cable), it requires 15 milliseconds on a computer with an Intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM, and 64 bit Microsoft Window 8.1 operating system.

TABLE. 1 INTERVAL BETWEEN MINOR AXES vs. EXECUTION TIME

Interval between Minor Axes (km)	Execution time (msec)
1	1000
2	141
5	40
10	20
20	15

V. Conclusion And Discussion.

In this study, we focused on disaster-aware submarine fiber-optic cable deployment. Results from our study show that we can reduce expected cost associated with cable breaks prompted by disaster occurrence, which includes cost of repair, cost of cruising to the cable break location, and penalty due to bandwidth loss, significantly for a slight increase in deployment cost.

Although the ILP formulation provided above does provide optimal solution, it is confined to two nodes and elliptic shape of cables in a two-dimensional space. However, practical experience shows that (i) geographical constraints such as roughness of seabed, undersea valleys, sea depth, etc. are main determinants of shapes of the cables in a three-dimensional space, (ii) submarine cable systems consist of more than two nodes forming line, ring or mesh topology networks.

Thus, we can achieve a solution of higher precision by taking into consideration these geographical information in our approach as well as network topology. Consequently, our approach should incorporate both a three-dimensional space and multiple nodes in its methodology. In such a case, without any limitations, the solution space is too large to find an optimal solution. In our future work, these hurdles will be addressed, wherein we will consider mesh topology, irregular shape of cables and the topography of undersea environment in our methodology.

VI. Acknowledgment

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