Disaster-Aware Submarine Fiber-Optic Cable Deployment for Mesh Networks

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Abstract—With the increasing social and economic reliance on the Internet and the significant monetary and non-monetary societal cost associated with service interruption, network survivability is an important element in telecommunication network design. A major cause of Internet service interruption is breakage of fiber-optic cables due to man-made or natural disasters such as earthquakes. In addition to the societal cost, there is also cost of repairing damaged cables paid by the cable owner. A disaster-resilient submarine cable deployment can achieve significant cost saving when disaster strikes. In this study, we investigate a disaster-aware submarine fiber-optic cable deployment optimization problem to minimize such expected costs in case of a disaster. While selecting paths for the cables, our approach aims to minimize the expected cost for both cable owner and the affected society, considering that submarine fiber-optic cables may break because of natural disasters, subject to limitation of available deployment budget and other constraints. In our approach, localized disaster-unrelated potential disconnection (e.g., due to shark bites) are avoided by providing a backup cable along with primary cable. We consider a mesh topology network with multiple nodes located at different sea/ocean shores, submarine fiber-optic cables of irregular shape, and a topography of undersea environment. We present an Integer Linear Program to address the problem, together with illustrative numerical examples. Finally, we validate our approach by applying it to a case study of an existing cable system in the Mediterranean Sea, and the results show that we can significantly reduce overall expected cost at a slight increase in deployment cost. The results demonstrate a potential saving of billions of US dollars for the society in case of a future disaster. In order to achieve such large savings, cable companies may require to lay somewhat longer cables to avoid potential disaster areas, which may increase deployment cost that is relatively smaller compared to potential savings in case of a disaster. Understanding such trade-offs is important for stakeholders, including government agencies, cable industry, and insurance companies, which may have different objectives, but can work together for the overall benefit of the society.

Index Terms—Submarine fiber-optic cable, undersea disaster, disaster resiliency, network-design optimization.

I. INTRODUCTION

The installation of the first transoceanic fiber-optic cable in 1988, which connected Britain, United States of America, and France, was an important event in the Internet revolution. It provided means for cost-effective data transmission at high rate over long distances that was not available before. Currently, submarine fiber-optic cables and their terrestrial counterparts carry about 99% of global Internet traffic [1]. Accordingly, both global and local network connectivity heavily depend on submarine fiber-optic cable systems.

Nowadays, we have become increasingly dependent on the Internet. It greatly impacts almost all aspects of our lives. However, despite our dependence on the Internet, there exists a general lack of awareness of the indispensable importance of submarine fiber-optic cable systems, except when such cable systems fail. The principal causes of submarine fiber-optic cable failures are due to shark bites and human activities such as fishing, shipping, anchorage, as well as natural disasters such as earthquake, hurricane, and tsunami.

External aggressions associated with human activities prompt about 70% of total submarine fiber-optic cable faults. Moreover, statistics reveal that 75% of all submarine fiber-optic cable faults occur in water depths shallower than 200 m, mainly due to human activities [2]. The conventional approach to reduce this type of failures involves provisioning of additional shielding as presented by [3]. Natural catastrophes, such as earthquake, hurricane, tsunami, and tornado, constitute about 10% of total submarine fiber-optic cable failures. When focusing on deep-water environment, natural disasters cause at least 31% of submarine fiber-optic cable failures [2]. While failures due to human activities normally cause a single cable failure so that network connectivity can be maintained during the time the cable is repaired, failures due to natural disasters may affect many cables simultaneously which in turn may cause regional Internet shutdown with grave consequences.

Research to address the problem of submarine cable failure consider faults prompted by human activities, while ignoring natural disasters, perhaps because we are often guided by heuristics and rules of thumb to address disaster planning [4]. There is insufficient research on network design methods to address the problem of natural disasters, which have detrimental economic impact to the submarine fiber-optic cable industry (cable owners, network operators, Internet service providers) as well as Internet users. In this study, we investigate a disaster-aware network of undersea fiber-optic cables.

Below, we present several examples of natural disasters in terms of failures of submarine fiber-optic cables and their consequences that motivate the importance of a disaster-aware submarine cable deployment approach.

The Pingtung (aka Hengchun) earthquake of magnitude 7.0 in 2006, in Taiwan prompted mud flows and submarine landslides that travelled over 246 km at a depth greater than...
4 km, consequently breaking 22 submarine fiber-optic cables [5]. Internet, data, and telephone systems were detrimentally affected in China, Taiwan, Macao, Hong Kong, and other countries. Cable-repair activities lasted for seven weeks.

Ref. [2] presents different natural disasters that have occurred in different regions together with their effects to submarine fiber-optic cables, viz: (i) in 2003, the Boumerdes earthquake of magnitude 6.8 occurred in Algeria, triggering landslides and turbidity currents, which damaged six submarine fiber-optic cables. Consequently, all submarine fiber-optic cables systems found in Mediterranean region were affected. (ii) The Andaman-Sumatra earthquake in 2004 generated tsunami in Indian Ocean that travelled over 3,000 miles away from the epicenter. About 18 countries were affected and land-based telecommunications networks were damaged in coastal area of Malaysia and South Africa. (iii) The 2009 Typhoon Morakot in Taiwan prompted sediment-laden flows that broke at least nine submarine fiber-optic cables.

The Great East Japan Earthquake of magnitude 9.0 off the coast of Japan in 2011 destroyed telecommunication infrastructure [6]. Letting the Nippon Telegraph and Telephone Corporation (NTT)’s 2700 km of cables swept away, and 1.5 million circuits for fixed lines and 4900 mobile base stations severely damaged.

Research by the Swiss Federal Institute of Technology (ETH) Zurich revealed that, if there is an Internet blackout in the entire country of Switzerland that lasts for one week, the country will experience a monetary loss of over 1.2% of its GDP [7]. Implicitly, submarine fiber-optic cable breaks caused by natural disasters may cause significant economic loss.

A. Related Work

Refs. [3], [8]-[12] address disaster-resilient network design and traffic engineering, and their focus is on impacts of natural disasters to terrestrial networks and cables buried underground. Ref. [13] presents a disaster-resilient network design where the focus is on network survivability and cable-shape aspects in submarine environment. This study does not consider detailed monetary loss associated with a given disaster.

A spatial design of a physical network robust against earthquakes is proposed by [11], in which three rules are stipulated: a shorter zigzag route, additive performance metric, and probability that all nodes intersect the disaster area is not reduced by additional routes within a ring network. In [12], the author proposes a geometric model of a network affected by a disaster. This can be useful in evaluating performance metrics of a network such as reliability and resiliency.

B. Our Contribution

Unlike [11]-[13], our approach minimizes the expected costs incurred by submarine fiber-optic cable owners due to restoration, considering the shape of the cable, topography of submarine environment, and probability of occurrence of a natural disaster in submarine environments. To the best of our knowledge, we present a unique optimization which is different from published research on optimization problems associated with disaster survivability of a network of fiber-optic cables. Moreover, we present a unique concept, wherein we discuss both the design from the point of view of the telecommunication provider and of the society (the customers), unlike [11]-[13] which consider the design from the point of view of telecommunication providers only.

Our study considers the cost incurred by submarine fiber-optic cable owners to restore network service to a normal condition when submarine fiber-optic cables break because of natural disasters. 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. Our approach significantly minimizes such losses in case of a disaster at the expense of an increase in deployment cost.

The goal of this study is to provide understanding of the tradeoff between disaster survivability vs. cost by numerical examples and results for certain case studies. Such understanding will help a discussion between different stakeholders, including government agencies, cable industry, and insurance companies, which may have different objectives, but can work together for the overall benefit of the society.

II. PROBLEM DESCRIPTION AND ASSUMPTIONS

![Fig. 1. Example of two landing stations connected by primary and backup cables.](image)

We consider the problem of connecting continents or islands (or landmasses) by submarine fiber-optic cables, wherein the water body separating the landmasses is susceptible to natural disasters. In this study, we present a protected connection between the landmasses by connecting each pair of communicating nodes by two submarine fiber-optic cables.

We consider the problem of the best way to connect nodes located on the beaches of the land parts (or islands) as shown in Fig. 1. The assumption that the nodes are located on the beaches is made for ease of exposition, but without loss of generality. 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 some straightforward modification in the formulation. In any case, our solutions for the simpler case can be easily extended to the case where the nodes are located inland. Note that avoiding disaster zones may require longer paths to lay cables and therefore increase
cable-deployment. This enables us to improve network disaster survivability without incurring additional cost to network operator. In addition, we can also further improve survivability if the budget increases.

Various shapes of cable can be employed to provide connection between the two nodes, such as rectangular, circle/ring, triangular, elliptical and random shapes. Topology optimization of undersea cables has been studied by [13], where various cable shapes are considered including rhombus, rectangular, and a rectangle with round corners. Work on optimizing the path of laying a single cable between two end-points appear in [43][44]. In [14], the authors present a survey on existing research publications related to disaster survivability in optical networks, where they classify disasters according to the following three categories: predictable, non-predictable, and intentional attack based on their characteristics and impacts on networks. Disaster modeling approaches can be divided into deterministic and probabilistic models [14]. A deterministic model assumes that network equipment fails with probability 1 if it is located within a disaster zone, and it fails with probability 0 otherwise. In contrast, in probabilistic model, a network equipment fails with a certain probability, depending on factors such as its distance from the disaster’s epicenter, dimension of the equipment (e.g., length of fiber cable), and specifications (e.g., the strength and reliability of the material, the level of shielding [3]). Relative to the deterministic model, probabilistic model introduces a certain level complexity. However, it improves accuracy by considering a range of realistic factors when evaluating the response of the cable to the natural disasters. Therefore, in this paper, we adopt a probabilistic approach.

Probability of cable failure in case of a disaster is required in order to apply our proposed approach. In this paper, as in e.g., [15], we rely on existing research in the field of earthquake engineering and assume that this probability is known. The determination of failure probability is extensively studied in [16], where the authors provide a vulnerability map based on failure probabilities of fiber links considering the distance of network component from a possible disaster epicenter. They also claim that the regions of possible disasters can be determined by using seismic hazard maps and by using grid partitioning. A similar approach is adopted by [17] where the authors also use seismic hazard maps to determine the possible disaster zones. They consider that areas that have higher peak ground acceleration are more prone to disasters (shown in Fig. 2). Besides earthquakes, disaster zones for other types of disasters is also provided in [18].

In addition to existing work that provides correlation between seismic movements and cable failures in telecommunication networks [16]-[24], there is also extensive research (e.g., [25]-[32]) focused on correlation between seismic movements with failures on other types of networks (e.g. gas pipelines) which can also be applied to optical networks. Exact calculation of failure probability of a component should consider the specifications such as material used, shielding, flexibility, surrounding conditions (e.g., the type of soil that a cable buried in), some of which are vendor-dependent. Since the focus of our work is to provide disaster-aware cable deployment and failure probability of a component is a given parameter, we consider a more basic approach as follows. The failure probability of a network component is computed based on the distance of the component from the disaster epicenter and it is assumed to follow a certain given function, which decays as the distance of the component from the epicenter.

![Fig. 2. Disaster zones that may affect a backbone network shown over a seismic hazard map [17].](image-url)
Finally, to minimize the probability of simultaneous cable breaks due to the occurrence of a natural disaster, Ref. [13] proposes a rectangular topology. However, in practice, submarine fiber-optic cables have irregular shapes. Fig. 1 also shows candidate primary and backup cables connecting landing stations, and the water body separating the landing stations is susceptible to a natural disaster where we assume that its effect can be characterized by an irregular circular disc (as shown in the figure).

In this study, we address the problem by considering practical settings. 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 (3D) space, and (ii) submarine cable networks connect more than two nodes. Thus, we consider geographical information in our approach as well as general network topology. Consequently, our method should cover both a 3D space and multiple nodes. Our method can be helped by the use of a shortest-path algorithm in 3D or commercial software such as Makai Plan [33], which provides the potential candidate primary and backup cables connecting stations is susceptible to a natural disaster where we assume that its effect can be characterized by an irregular circular disc (as shown in the figure).

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Henceforth, in this study, we consider a mesh network topology \( G(V, E) \) where \( V \) is the set of nodes and \( E \) is the set of links of heterogeneous bandwidth capacity denoted by \( N_e \) for each link \( e \in E \). The topology comprises a set of optical fiber cables connecting islands or continents. Each pair of adjacent nodes is connected by primary and backup cables. A sample topology with corresponding cable-path pairs is shown in Fig. 3. A network cut is referred to as the disruption of connectivity mainly due removal or failure of a link or node in a network [34]-[36].

![Fig. 3. Example mesh topology with each link consisting of two cables.](image)

Our problem is to select primary and backup cable routes among the candidate routes for each link considering possible disasters with the aim to minimize expected cost in case a disaster happens. We also consider the connectivity of the topology, i.e., when multiple cables break due to a disaster, any node pair should still be able to communicate through the survived network. This is depicted in Fig. 3, where primary and backup cables which connect four nodes fall within the same disaster zone.

### III. Problem Formulation

We provide an Integer Linear Program (ILP) formulation for our problem, as follows.

**Given:**

\( G(V, E) \): mesh network topology, where \( V \) is the set of nodes and \( E \) is the set of links of heterogeneous bandwidth capacity denoted by \( N_e \).

\( Q_e \): set of candidate routes for each link \( e \in E \), which can be obtained by using software such as Makai Plan [33]. These routes are of irregular shape considering the topography and geographical constraints of the submarine environment.

\( \Omega \): set of possible disasters characterized by their location and strength. The epicenter of a disaster is typically located near earthquake faults.

\( F_{e,n} \): probability that cable \( i \) breaks, if disaster \( n \in \Omega \) occurs and route \( r \in Q_e \) is selected in link \( e \in E \). As mentioned above, the probability of failure in case of a certain disaster can be computed by the approaches described in [15]-[24].

\( L_{e,n,r} \): length of cable part damaged by disaster \( n \in \Omega \), when route \( r \in Q_e \) is selected in link \( e \in E \), and \( r \) passes through \( n \), as depicted in Fig. 2.

\( L_{e,n,r} \): cruising distance from offshore to the damaged part for link \( e \in E \), for route \( r \in Q_e \), and for disaster \( n \in \Omega \), as depicted in Fig. 3.\(^1\)

\( L_r \): length of route \( r \in Q_e \) in km.

\( N_e \): bandwidth capacity of cables in link \( e \).

\( T^2 \): expectation of time to repair cable \( i \) in link \( e \in E \).

\( C_d \): cost of cable deployment per km.

\( C_g \): cost of repair per km.

\( C_s \): shielding cost per km. In this context, shielding refers to strengthening cables or providing protecting materials to resist physical attack from external aggressions [3].

\( C_l \): cruising cost per km.

\( C_p \): penalty per bandwidth, per unit time due to breach of service level agreement (SLA) which is a contract between service providers and users defining the level of service expected from the service providers and other users’ obligations. \( \gamma \): deployment and shielding budget.

\( \delta \): acceptable minimum distance separating primary and backup cables further than 200 km from offshore based on findings from [37]. Note that this distance marks the beginning of deep sea.

\( X_{r,e,n} \): a pre-computed value such that it is 1, if route \( r \in Q_e \) is selected for link \( e \in E \), and \( r \) passes through disaster zone \( n \in \Omega \), otherwise it is 0.

\( W_{r_1,r_2} \): nearest distance in km between routes \( r_1 \) and \( r_2 \) for link \( e \in E \), and \( r_1, r_2 \in Q_e \).

\( K \): set of network cuts.

\( E_k \): set of links in \( k \in K \).

\( EDT^1_{e,i} \): expected downtime if route \( r \in Q_e \) is selected for cable \( i \) in link \( e \in E \).

\( \varphi \): subscribers’ cost per unit down time.

**Variable:** \( R_{e,i} \): binary variable, which is 1, if route \( r \in Q_e \) is selected for cable \( i \) in link \( e \in E \), 0 otherwise.

\(^1\)For simplicity, we assume that repair vehicles are close to offshore. In practice repair vehicles may be roaming or waiting in the sea.
Objective function:
The objective of this study is to minimize cost. Cost can be considered only as network operator's cost or as global cost, namely, sum of network operator's cost and subscribers' (social) costs. Thus, we consider two problems: minimize expected network operators' cost and minimize expected global cost (sum of network operators’ cost and subscribers’ cost). Expected network operators’ cost in this context is the sum of expected repair cost, expected cruising cost, and expected capacity loss cost by considering occurrence of natural disasters.

A. Expected Restoration Cost

Components of expected restoration cost follow:
a. Expected repair cost (ERC)
For each link \( e \in E \) in a network, we compute expected repair cost (ERC) as the product of repair cost per unit length, the length of damaged part of the cable by disaster \( n \in \Omega \), and the probability of cable failure:

\[
ERC = \sum_{n \in \Omega} \left( \sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} C_e \times L_{e,n,i}^r \times R_{e,i}^r \right) \times P_{e,i}^r \tag{1}
\]

b. Expected cruising cost (ECC)
\( ECC \) is the product of cruising cost per unit length, cruising distance, and the probability of cable failure:

\[
ECC = \sum_{n \in \Omega} \left( \sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} 2 \times C_e \times R_{e,i}^r \times (L_{e,n,i}^r + L_{e,n}^r) \right) \times P_{e,i}^r \tag{2}
\]

c. Expected capacity loss cost (ECL)
\( ECL \) is the product of penalty per bandwidth, capacity of a link, link failure time, and the probability that both primary and backup cables of link \( e \in E \) fail due to disaster \( n \in \Omega \):

\[
ECL = \sum_{n \in \Omega} \left( \sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} 2 \times C_p \times N_e \times X_{e,i}^{r_1,n} \times X_{e,i}^{r_2,n} \times T_e \times R_{e,i}^r \right) \times P_{e,i}^{r_1,n} \times P_{e,i}^{r_2,n} \tag{3}
\]

Note that Eqn. (3) is not linear since we have product of two binary variables. We can linearize it by introducing an auxiliary variable \( S_{e,r_1,r_2}^r \) defined as:

\[
S_{e,r_1,r_2}^r = R_{e,r_1}^r \times R_{e,r_2}^r \ \ \forall e \in E, \ \forall r_1 \in Q_e, \ \forall r_2 \in Q_e, r_1 \neq r_2 \tag{4}
\]

Subject to the following constraints:

\[
S_{e,r_1,r_2}^r \leq R_{e,r_1}^r \ \forall e \in E, \ \forall r_1 \in Q_e, \ \forall r_2 \in Q_e, r_1 \neq r_2 \tag{5}
\]

\[
S_{e,r_1,r_2}^r \leq R_{e,r_2}^r \ \forall e \in E, \ \forall r_1 \in Q_e, \ \forall r_2 \in Q_e, r_1 \neq r_2 \tag{6}
\]

\[
S_{e,r_1,r_2}^r \geq R_{e,r_1}^r + R_{e,r_2}^r - 1 \ \forall e \in E, \ \forall r_1 \in Q_e, \ \forall r_2 \in Q_e, r_1 \neq r_2 \tag{7}
\]

Thus, the expected capacity loss cost can be re-written as:

\[
ECL = \sum_{n \in \Omega} \left( \sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} 2 \times C_p \times N_e \times X_{e,i}^{r_1,n} \times X_{e,i}^{r_2,n} \times T_e \times S_{e,r_1,r_2}^r \right) \times P_{e,i}^{r_1,n} \times P_{e,i}^{r_2,n} \tag{8}
\]

Now, we formulate the objective as follows:

\[
\text{Min} \ (ERC + ECC + ECL) \tag{9}
\]

Subject to:

a. Cable deployment and shielding budget constraint:
Deployment and shielding cost for the network must not exceed budget \( \gamma \). Note that a route that passes through a possible disaster zone may have to be selected if there are no other options. In this case, this part will be vulnerable. Ref. [3] investigated the minimum cost of shielding a network to guarantee connectivity subject to human activities or natural catastrophes such hurricanes, earthquakes, tsunami, etc., wherein it proposed shielding vulnerable parts of the link or path. Since shielding the whole submarine cable system is not cost effective, our approach guarantees connectivity at a minimum cost by shielding parts of submarine fiber-optic cables that pass through possible disaster zones \( L_{e,i}^{r,n} \). Thus, the deployment cost constraint is evaluated as:

\[
\sum_{n \in \Omega} \sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} (C_d \times L_e \times R_{e,i}^r) + \sum_{n \in \Omega} \sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} (C_S \times L_{e,n}^r \times R_{e,i}^r) \leq \gamma \tag{10}
\]

Where the first term provides deployment cost, and the second term gives shielding cost.

b. Route uniqueness constraint:
Only one candidate route has to be selected for each cable:

\[
\sum_{r \in Q_e} R_{e,i}^r = 1 \ \ \forall i; i \geq 1, \ \forall e \in E \tag{11}
\]

c. Route disjoint constraint:
Primary and backup cable routes must not intersect at any point:

\[
W_{e}^{r_1,r_2} \times S_{e}^{r_1,r_2} \geq \delta \ \forall e \in E, \ \forall r_1, r_2 \in Q_e, r_1 \neq r_2 \tag{12}
\]

d. Connectivity constraint:
Connectivity concept is used in virtual topology design to ensure that a physical link failure does not cause failures of virtual links in the same network cut. Similarly, to ensure connectivity of a network, we require that cables of the links that are in the same cut should not go through the same disaster zone. Otherwise, when a disaster occurs, it may break all the
cables whose associated links are in the same cut, and so the topology would be disconnected. Thus we need:

$$\sum_{e \in E} \sum_{i \in \{1, 2\}} \sum_{r \in \Omega_n} X_{e,i}^{n,2} \times R_{e,i}^r \leq 2 \mid E_k \mid$$

$$\forall k \in K, \forall n \in \Omega$$ (13)

e. Constraints due to linearization:

These constraints are introduced in Eqns. (5), (6), and (7).

Number of variables in this ILP is $|E| \times (I \times R + R^2)$ and number of constraints is $3 \mid E \mid \times (I + R^2) + 1 + \Omega$, where $I$ is the number cables for each link (e.g., 2 in our approach) and $R$ is the number of candidate routes for each cable.

B. Expected Global Cost

Observe that, if cables break, it is not only the network operator that incurs additional costs. It is the whole society that suffers from Internet shutdown. Downtime costs associated with telecommunication infrastructure failures vary significantly within industries, type of services issued, countries, and end users. The core factor for this variation is different effects of the downtime. Other factors for this variation include size of the business and duration of service restoration. Thus, it is difficult to measure the cost of telecommunication infrastructure failures considering global loss. However, practical experience shows that the cost is acute as the survey conducted by CA Technology (in North USA and Europe which involved 200 companies) found that more than $250 billion in revenue is lost each year due to telecommunication downtime [38]. This translates to $150,000 annual loss for each business surveyed [38]. Recall also the Swiss study [7] that estimated the global cost as 1.2% of GDP due to Internet shutdown in Switzerland. We revamp our formulation to address the issue of expected global cost by adding a new parameter $SC$ which denotes subscribers’ cost to our objective function in Eqn. (9), which is defined as follows:

$$SC = EDT_{e,i}^r \times \varphi \times R_{e,i}^r$$ (14)

Henceforth, the new objective function is as follows:

$$Min (ERC + ECC + ECL + SC)$$

Subject to Eqns. (10), (11), (12) and (13).

IV. ILLUSTRATIVE NUMERICAL EXAMPLES

We conducted numerical simulations to evaluate our approach on mesh network topologies with irregular cable shapes for different dimensions of clustering coefficient of a network\(^2\), different radius sizes of disasters, different number of routes, and different link lengths. All parameters used in our simulations are determined by information from public sources [40]-[42], and they 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. Mean time to repair is 168 hours, penalty due to capacity loss is 100 per Tbps, and each link assumes heterogeneous bandwidth capacity, whereby actual capacity of each link is uniformly distributed between 10 and 100 Tbps. Recall that the failure model adopted in this study is the probabilistic failure model, hence probability of equipment failure is assumed to depend on its distance from disaster’s epicenter and to follow a normal distribution with a mean of 0 and a standard deviation of 1.

Ref. [37] investigates the minimum distance at which an alternate facility should be placed to ensure service reliability, where different categories of disasters such as hurricane, storm and snow, earthquake, volcano, tsunami, and terrorism are considered. Records from this study show that hurricane recorded a maximum distance of 105 miles whereas storm and snow, earthquake, volcano, and tsunami recorded 68, 60, 75, and 51 miles of minimum distance, respectively. Considering that our focus is on earthquake, we assume the maximum distance of cable separation is 110 km (determined based on [37]), because this distance is sufficient to achieve a solution of higher precision, i.e., the marginal benefit of increasing the distance between two cables beyond 110 km is negligible.

We investigate the results of our study by using 11 different clustering coefficient varying between 0.05 to 1.0, by considering 13 different radius sizes for disaster zones varying between 10 km to 130 km, and by limiting the number of routes with a value between 15 and 45. For each clustering coefficient, disaster zone radius, and number of routes, we randomly place the nodes, generate and locate disaster zones and provide the route paths, then we run our simulation. We rerun each simulation 50 times set, and the results shown below are average of the results obtained with 95% confidence interval.

Finally, we compare Disaster-Aware Cable Deployment (DADC), which has two types DACD-NC (DACD that minimizes network operators cost) and DACD-GC (DACD that minimizes global cost), against Disaster-Unaware (DUCD) approach which minimizes deployment cost only. Note that the latter one (DUCD) also deploys a primary cable along with a backup cable for each link by keeping them apart with some certain distance (so it is protected against single cable failures), but it does not consider disaster failures and only minimizes deployment cost. Comparison of these approaches is based on percentage reduction in expected cost (expected restoration cost and global cost) and percentage increase in deployment cost. The results shown below provide a comparison to a baseline approach, namely DUCD. However all the results are achieved without exceeding the budget determined by the network operator as ensured in Eq. (10). Monetary values of total deployment cost range in hundreds million US dollars depending on the length of the cable [40]-[42]. We consider an estimated monetary value of the deployment budget as $190 million, which is the estimated deployment cost of MedNauitilis subsystem, a 5-node 13-cable subsystem [41] that we investigated in Section V as a case study.

A. Clustering Coefficient vs. Costs

In Fig. 4, we show expected and deployment costs for different clustering coefficients considering DACD-NC and DACD-
In this case, DACD-GC reduces both expected global and restoration cost between 90% and 100%. On the other hand, DACD-NC reduces between 89% and 95% of expected restoration cost while reduction in terms of expected global cost lies between 8% and 15%. Moreover, both DACD-NC and DACD-GC reduce more expected cost as clustering coefficient increase because of increase in number of links. Deployment cost increases for both approaches as the clustering coefficient increases, because we need to deploy more links. However, the increase in deployment cost is higher for DACD-GC because long route are necessary to avoid deploying cables in disaster zones for each link. We observe that DACD-GC requires more deployment cost than DACD-NC, but in return it reduces subscribers’ cost significantly. The reader may ask whether it is justified to increase the deployment cost for a rare event like earthquakes. However, if a disaster strikes, then the savings on cost to the society, as well as on restoration cost, would be several orders of magnitude higher than the additional investment required on cable deployment to avoid disaster areas. With current monetary values [39]-[42], savings on global cost in case of a disaster can be up to 2 billion US dollars for DACD-GC and 0.8 billion for DACD-NC. To achieve such savings, the cables may take longer routes and because of that the additional cable deployment cost will be up to 60 million US dollars. These numerical figures provided here have the potential to initiate a discussion between stakeholders such as cable companies, government bodies, and insurance companies. Considering $2 billion benefit to society in case of a disaster, $60 million additional budget can be an acceptable cost and can be negotiated between stakeholders. For example, a government may choose to subsidize a significant part of the additional deployment cost.

**B. Radius size vs. Costs**

Figure 5 presents the results of expected and deployment costs using different dimension of radii of disaster zones. Reduction in expected restoration cost and global cost lies between 90% and 100% for DACD-GC. DACD-NC reduces between 89% and 95% of expected restoration cost whereas reduction lies between 10% and 20% for expected global cost. Thus, DAC-GC performs better in either case compared to DACD-NC which performs poor for expected global cost. However, reduction of expected cost in either case decreases as the radius size increases because of large dimension of disaster zones. Moreover, the increase in deployment cost of either approach is proportional to the increase in radii of disaster zones because, when the disaster zone is large, it is possible to avoid deploying a cable in a disaster zone by using a long route which in turn increases deployment cost. In this case, we also observe that DACD-GC requires more deployment cost than DACD-NC, but in return it reduces subscribers’ cost significantly.

**C. Number of Routes vs. Costs**

We investigate effects of number of routes in the problem, by running simulations on varying number of routes, and the results are depicted in Fig. 6. DACD-NC records low value in terms of expected global cost ranging between 8% and 18% whereas expected restoration cost lies between 92% and 97%. On other hand, DACD-GC records higher values in either expected restoration cost or expected global cost, wherein the reduction lies between 82% and 98%. Moreover, both DACD-NC and DACD-GC reveal more positive results as number of candidate routes increases. Results show that increase in deployment cost decreases as the number of routes increases. This is due to the fact that, with increasing number of routes, finding a solution close to optimal is more likely.

**D. Clustering Coefficient vs. Execution Time**

We investigate execution time of our approach as shown in Fig. 7, where we present execution time of our approach for
different dimensions of clustering coefficient. It is apparent that execution time increases as the clustering coefficient increases, e.g., from 20 sec when clustering coefficient is 0.05 vs. 660 sec when clustering coefficient is 1 for DACD-NC, and from 50 sec when clustering coefficient is 0.05 vs. 1000 sec when clustering coefficient is 1 for DACD-GC on a computer with an Intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM, and 64 bit Microsoft Window 8.1 operating system. The increase in execution time is due to the increase in number of links in a network.

Fig. 7. Clustering coefficient vs. execution time.

V. A CASE STUDY

We evaluate our approach by considering MedNautilus submarine fiber-optic cable system [25] shown in Fig. 8, which consists of seven landing stations viz: AG, CI, CG, HI, IST, PC, and TI. The total length of this cable system is 7000 km. Mediterranean Sea is susceptible to earthquakes that have caused huge damages to submarine fiber-optic infrastructures. Nevertheless, this region is vital for connecting Eastern Mediterranean countries, Western Europe, Northern Africa, and Asia. Currently, about 13 submarine fiber-optic cable systems pass through the region. The disaster zones shown in Fig. 8 by dotted cycles are natural disasters which occurred previously in this region according to seismic hazard maps.

Fig. 8. MedNautilus cable system found in Mediterranean basin.

We investigate the problem by using 25 routes for each link, and then we report results for expected and deployment cost of each link as shown in Fig. 9. Results demonstrate that reduction in expected costs considering both global and restoration cost for DACD-GC lies between 90% and 99%. On the other hand DACD-NC reduces between 86% and 92% of expected restoration costs; and it reduces between 20% and 30% of expected global cost. Considering monetary values based on [39]-[42] for all the cost parameters we considered ($C_d, C_x, C_s, C_t, C_p$), savings on global cost in case of a disaster can be up to 0.5 billion US dollars for DACD-GC and 0.3 billion for DACD-NC with a much smaller increase in cable deployment cost that is around additional 28.5 million US dollars. Recall that as budget limit, we consider $190 million [41] that was estimated for the system shown in Fig. 8, which is $30 million more than what we achieved by DUCD. We acknowledge that we did not consider the areas that cable designers need to avoid (e.g., ecologically critical or financially important areas), a data that we do not have access. Nevertheless, we still demonstrate significant savings in case of a future disaster for the society as well as for the cable owner.

Observe that there is about 5% to 15% increase in deployment cost for both DACD-GC and DACD-NC which is attributed to avoiding cable deployment in disaster zones. Apart from that, link 5 that connects CI and TI, records higher value in terms of deployment cost because of the long distance separating the two landing stations. Also, there is a fluctuation of reduction in expected cost, that is attributed to the location of landing stations and the location of epicenters of natural disasters. For instance, link IST-AG records low values in terms of reduction in expected cost since this location is susceptible to a number of natural disasters and the width of Marmara Sea is narrow to the extent that it is practically impossible to avoid deploying the cable in a disaster zone. Nevertheless, our approach minimizes this effect by deploying the cable in zones with less effect, since we model the disaster by using a probabilistic model.

Figure 10 depicts a particular example of natural disasters that have occurred in deep sea of Mediterranean Sea. Since the aim of this study is to address submarine fiber-optic failures due to natural disasters in deep sea, we apply our approach to these disasters, and in particular we consider four links that go through these natural disasters. Links for consideration in this

Fig. 9. DACD-GC and DACD-NC results for MedNautilus submarine fiber-optic cable system.
framework are CI-CG, CG-HI, CI-TI and IST-AG. Using our approach, the expected cost of this system can be reduced significantly (i) by providing protection (backup cable) for each link and (ii) avoiding deploying cable in disaster prone areas as shown in Fig. 10. We present the results in Fig. 11 for these links, where we consider both expected global and restoration cost as well as increase in deployment cost for each link. Results from Fig. 11 show that reduction in expected cost considering both global and restoration cost for DACD-GC lies between 88% and 97%. DACD-NC reduces between 86% and 92% of expected network operators’ cost. However, DACD-NC reduces between 15% and 25% of expected global cost, a practical disadvantage. As shown in Fig. 11, increase in deployment cost for both DACD-GC and DACD-NC lies between 5% and 15% because of long route taken to avoid deploying submarine fiber-optic cables in disaster zones.

In this case, link CI-TI records low value in terms of reduction in expected cost for both DACD-GC and DACD-NC compared to other links because this link is prone to two natural disasters that are located in deep sea: thus CI-TI suffers long repair time as well as high reparation cost. Similarly, this link records high value of increase in deployment cost because the distance separating the two landing station is long.

VI. COST SENSITIVITY ANALYSIS

We conduct cost sensitivity analysis to evaluate the impact of change in deployment, cruising and repair cost to the results of our approach. We conduct partial sensitivity analysis wherein we move each input variable while keeping other variables at their normal values; then, we return the variable to its normal value and repeat the process for each input variable in a similar way. Next, we observe effects of these changes to the results of our approach. In this case, we use different values of deployment, cruising, and repair costs ranging between -100% and 100% of normalized values of each cost. We run the simulations 50 times for each value and to each variable, and record the average results in each case as shown in Fig. 12 and Fig. 13.

We show the effect of changes of each cost on DACD-NC in Fig. 12. Results show that repair cost is the most determining factor of expected cost for DACD-NC followed by cruising cost. Shielding cost is the least determining factor of expected cost for DACD-NC.

We show the effect of changes of each cost on DACD-GC...
in Fig. 13. In this case, subscribers’ cost per unit down time is the most determining factor of expected cost mainly due to the long time taken to restore services (long repair time) when there is submarine fiber-optic cable failures. As shown in Fig. 13, repair and cruising costs follow the perching order because of high repair cost and long cruising distance encountered. Observe that shielding cost is also the least determining factor of expected cost for DACD-GC because changes in shielding cost do not cause large changes of expected cost simply because we rarely apply shielding.

Conclusively, subscribers’ cost per unit down time is the most determining factor of expected cost followed by repair and cruising cost for DACD-GC, whereas shielding cost is the least factor influencing expected cost for both DACD-GC and DACD-NC. Nevertheless, for DACD-NC, repair and cruising cost are the most determinant factor of expected cost.

Since the cruising cost depends on oil prices, the rapid variation on cruising cost is suspected to especially affect the savings in case of a disaster. We investigate the change in savings if the cruising cost varies. The results are shown in Fig. 14. We observe that if the cruising cost increases, there will be more savings for both DACD-NC and DACD-GC. For instance, the numerical examples show that if the cruising cost is double of its current values, then the savings will increase by 55% compared to savings with current values and become 1.24 billion and 3.1 billion US$ for DACD-NC and DACD-GC, respectively. However, if the cruising cost decreases, then the savings will be less than the savings with current cruising cost values. The results show that if the cruising cost is 3/4 of the current values, then the savings will decrease by 53% and become 376 million US$ for DACD-NC. For DACD-GC, in this case, the savings will reduce by 80% and become 400 million US$.

VII. CONCLUSION

In this study, we focused on disaster-aware submarine fiber-optic cable deployment. We presented a probabilistic model that mitigates the effects of natural disasters on submarine fiber-optic cables. First, we provided an Integer Linear Program formulation that addresses the problem in which we consider irregular shapes of submarine fiber-optic cables, mesh network topology, and the topology of submarine environment. In this context, the challenge is to avoid deploying submarine fiber-optic cables in disaster zones which in turn increases the deployment cost. We applied our approach to random mesh networks susceptible to random number and size of natural disasters and also to a case study for MedNautilus submarine fiber-optic cable system. Finally, we conducted cost sensitivity analysis aiming at studying the effects of fluctuation of input parameters of our model.

Illustrative numerical examples revealed that our disaster-aware approach that considers global cost (sum of subscribers’ cost and restoration cost in case of a disaster), DACD-GC, reduces both cost to the society and cost of restoration significantly. On the other hand, the disaster-aware approach that only minimizes network operator’s restoration cost (DACD-NC) provides savings in restoration cost (due to repair, cruising, and capacity loss) of between 89% and 95% compared to the disaster-unaware approach. To achieve such savings, cables may take longer routes, so the deployment cost increases by 5% to 15%. Note that even with DACD-NC that does not directly minimizes global cost, we still achieve additional savings in global cost as a by-product of between 8% and 15%. This result shows that if the network operators consider only their benefit, and use DACD-NC, they still save on global cost. However, by laying cables aiming to minimize global cost, a further significant reduction on the cost to the society can be achieved (up to 97% compared to disaster unaware...
approach). For this case, additional deployment cost to achieve savings on global cost are very close to those of DACD-NC. Accordingly, our approach can provide valuable information about tradeoffs between deployment cost, expected restoration cost and global cost due to a natural disaster and demonstrate significant global cost vs. relatively much smaller investment. Trading off potential increase in deployment cost to achieve savings on global cost are very close to those of DACD-NC.

Accordingly, our approach can provide valuable information about tradeoffs between deployment cost, expected restoration cost and global cost due to a natural disaster and demonstrate significant global cost vs. relatively much smaller investment. Trading off potential increase in deployment cost to achieve savings on global cost are very close to those of DACD-NC.

REFERENCES


