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A Seismic Resistant Design Algorithm for Laying and Shielding of Optical Fiber Cables

Zengfu Wang, Qing Wang, Moshe Zukerman, Fellow, IEEE, Bill Moran

Abstract— This paper considers a long-haul optical fiber cable, connecting two points on the Earth’s surface that passes through earthquake-prone or other sensitive areas. Different segments of the cable are characterized by different protection levels, where a higher level through shielding represents a more costly and more resilient segment. This leads to a multi-objective optimization problem where the two objectives are: (1) total cost of the cable, and (2) total number of potential repairs along the cable likely to be caused by earthquakes. As a measure of seismic risk we use the concept of cable repair rate used in the civil engineering community. In our models, ground motion intensity data are used to estimate the cable repair rate, and a graph of a triangulated irregular network is used to represent the Earth’s surface. We formulate this optimization problem as a multi-objective shortest path problem and solve it by a variant of the label setting algorithm. Two approximate algorithms, an interval-partition-based label-setting algorithm and an evolutionary algorithm are also presented as methods of computational cost reduction for large scale cases, and their results are compared. The solution leads to a Pareto front or an approximate Pareto front that enables us to choose the path and protection of the cable to either minimize cost for a given risk level or minimize risk for a given budget.

Index Terms—Optical fiber cables, path optimization, multi-objective optimization, cost effectiveness, seismic resilience.

I. INTRODUCTION

Long-haul optical fiber cables, are vital for transporting information critical for the operation of a modern society. According to the latest Submarine Cable Map updated by TeleGeography for 2016 [1], around 321 submarine telecommunication cable systems (293 in-service and 28 planned) with more than 550,000 miles carry over 99% of the international communications [2]. On the one hand, constructing such cables requires significant capital investment with a drive to minimize upfront costs. On the other hand, survivability under various disasters is also of significant importance since breakages can have severe social, economic and financial consequences.

A range of measures can be used to improve survivability of an optical fiber cable; specifically, special shielding or extra material can be added to enhance the robustness of the cable passing through high risk areas, or a path can be chosen that avoids such areas, or a combination of these measures can be used. This requirement is highlighted by the following example. In 2006, eight submarine telecommunication cables (APCN, APCN-2, C2C, China-US CN, EAC, FLAG FEA, FNAL/RNAL and SMW3) were damaged, with a total of 18 cuts, by the Hengchun earthquake [3]. As a consequence, Internet services in several Asian countries/regions including China, Taiwan, Hong Kong etc., were severely disrupted for several weeks [3]. For a modern society, largely reliant on the Internet, an Internet blackout for one week can lead to over 1% loss of annual GDP [4], [5]. Again in 2009, the same eight cables were destroyed by the Ryukyu Islands earthquake. However, TPE and TGN-IA, two new cables laid in 2008 and 2009, respectively, were not affected since they were deliberately laid a safe distance away from the Taiwan earthquake prone area. As a result, the impact of the 2009 earthquake was almost insignificant relative to that of the 2006 earthquake [3]. Of course, the damaged cables had to be repaired, but the consequences to users were minor.

In practice, there are several different approaches to cable shielding, expressed in terms of different protection levels available for cables. For example, several types of submarine fiber cables with different strengths of the armor are available and may be used in a submarine cable system according to the depth of the seabed where the cable lies [6]. The construction cost of a cable is an increasing function of the protection level, while the potential seismic damage is a decreasing function of its protection level.

Because of the increased cost of higher protection level of cables, it is important to identify the critical segments of the cable that are more likely to be damaged (for example, because they are located in higher risk areas), and strengthen those segments to increase overall cable survivability.

In this paper, we study the problem of optimizing the path and protection level for an optical fiber cable connecting two sites on the Earth’s surface. For ease of exposition, throughout most of this paper we only consider earthquake risks. However, in
Section [VI] we explain how our approach can be applied to consider other risks associated with cable laying that include natural hazards other than earthquakes, and human activities such as fishing, as well as to consider areas where cables cannot be laid, for example, areas where license for cables cannot be obtained, or areas of high ecological values. Henceforth, we use the terms \textit{laying} and \textit{construction} interchangeably to mean either laying or construction of cables. The related terms \textit{laying costs} include all direct and indirect costs associated with building, installing, laying and/or constructing the cable. These include cost of materials, labor used in cable production, transportation, licenses, etc.

For such a practically important problem, to the best of our knowledge, there is no other solution based on a rigorous approach or even a heuristic approach available in the literature. To address this gap, we provide a formulation of a multi-objective shortest path problem, where we aim to obtain all Pareto optimal paths for the cable with the following two objective functions. The first objective is the laying cost of the cable based on the length of the cable and the costs associated with the various protection levels used in high risk areas. The second objective is the risk of cable failure, quantified as the number of potential repairs along the cable as a result of earthquakes. This measure is commonly used in practice [7] as well as in the civil engineering literature [8] for this purpose because, firstly, the number is associated with the cost of reconstruction as well as business and societal costs of a failed cable and, secondly, it can be estimated from ground motion data, from which we can obtain the cable repair rate [9], [10], [11].

We use a \textit{triangulated irregular network} to approximate the Earth’s surface, and ground motion intensity measures of earthquakes, obtained either from available data (e.g. USGS (https://www.usgs.gov/)), or by Probabilistic Seismic Hazard Analysis (PSHA) [12] to estimate the cable repair rate. Based on this model, we solve the multi-objective shortest path problem by an extension of the known label setting algorithm. This enables us to obtain all the Pareto optimal solutions that provide considerable flexibility in cable route selection, taking into consideration the available protection levels and the trade-off between cost effectiveness and seismic resilience. For large scale path optimization problems with a huge number of non-dominated labels, an interval-partition-based label-setting algorithm and an evolutionary algorithm are used to derive approximate solutions and their results are compared. In summary, our novelty here is twofold:

- We apply, apparently for the first time, a multiple-protection-level repair rate model based on ground motion intensities, a landform model based on a triangulated irregular network, and a multiple-protection-level laying cost model for optimizing the path and non-homogenous construction of a cable.
- We apply the label setting algorithm to the multi-objective shortest path problem of minimizing laying cost while minimizing total number of repairs, again apparently for the first time.

The remainder of the paper is organized as follows. In Section [II] we discuss the state of the art and the related work. In Section [III] we introduce models of laying costs and cable repairs, and formulate the problem of minimizing laying cost and total number of repairs (a risk measure used in this paper) for cable design considering path planning and multiple protection levels. Next, leveraging on the label setting algorithm [13], our path planning algorithm is given in Section [IV] and two approximation algorithms are briefly introduced. In Section [V] simulation results of the three algorithms based on a 2D scenario and two real-world 3D data are presented. Then, in Section [VI] we discuss the extension of our approach to consider other hazardous and sensitive areas. In Section [VII] we give our conclusions from the work.

II. STATE OF THE ART AND RELATED WORK

Current approaches to path planning, or route selection for fiber optical cables between two locations, have focused on homogenous cables where, in our context, the number of protection levels is equal to one. In practice, the path planning procedures of cables have been implemented by traditional manual approach based on expert experience [7], [14].

In the traditional manual approach, using available data in a region of interest such as maps, aerial photographs etc., planners provide several relatively reasonable paths on the large-scale topographical map to connect the starting point and destination. Then a preliminary survey is conducted along the route of the path to verify the availability and rationality of the chosen path. If some constraints and obstacles cannot be eliminated or removed, alternative routes are chosen to be explored. The final path is determined by detailed analyses and comparisons. The primary characterization of traditional manual approach is the dependence on expert judgment and subjective analysis. A criticism of the traditional approach is that it may be far from optimal and especially when the decision space is large and complex.

A numerical solution based on Integer Linear Program for selecting paths from a candidate set for submarine fiber optic cables is presented in [15], which considered the expected cost for both cable owner and the affected society in case of a disaster. In [16], the Dijkstra’s shortest path algorithm is used to find the least accumulative cost path of a cable considering cost minimization and earthquake survivability. In [17], [18], path design for cables under specific and limiting assumptions about their shapes are proposed for a planar model. Based on seismic hazard information, Tran et al. [19] proposed a two-step approach to find appropriate geographical routes from candidate sets under a cost constraint to maximize the robustness of a network. Tran et al. [20] proposed a dynamic programming based algorithm that finds new cables and their routes to be added to a network with the aim to minimize the total end-to-end disconnection probabilities satisfying a given cost constraint. Saito [21] provided a node/link replacement strategy for a given planar physical network. In [22], we studied the problem of path optimization for a cable between
two locations on the surface of the Earth that crosses an earthquake-prone area. The problem has been formulated as a multi-objective variational problem and was solved using a continuous shortest path algorithm, known as the Fast Marching Method.

All the above mentioned publications, focused on path design of homogenous cables. To the best of our knowledge, the only work that has considered non-homogenous cables was the work of Zhang et al. [23], [24] that considered shielding of telecommunication cables in high risk areas. In particular, they considered the problem of deciding which cables required shielding in an existing communication network to guarantee network connectivity subject to minimum cost. They assumed that each cable has a given shielding cost and studied the problem under certain failure models. This is different from the problem addressed in this paper of path planning and laying of a single non-homogenous cable.

III. PROBLEM FORMULATION

We consider two points on the surface of the Earth between which the cable should be laid, or buried in shallow ground. We also consider a relevant geographic region of the Earth surface that includes the two points as well as all potential paths based on which Pareto front will be generated. The relevant geographic region denoted by $\mathbb{D}$ is assumed to be a closed and connected surface. We approximate the region $\mathbb{D}$ as a triangulated irregular network (TIN) [26], [27] in three-dimensional Euclidean space $\mathbb{R}^3$, which comprises irregularly distributed nodes determined by three dimensional coordinates $(x, y, z)$, where $z = \xi(x, y)$ is the elevation of geographic location $(x, y)$, and lines connecting pairs of nodes that are arranged as a tessellation of triangles. A graph $G = (V, E)$ is adopted to represent the TIN, where $V = \{v_1, v_2, \ldots, v_n\}$ is a finite nonempty set of vertices and $E = \{e_1, e_2, \ldots, e_m\}$ is a set of edges. Each vertex $v \in V$ is represented by a node in the TIN and every edge $e \in E$ corresponds to a line of the TIN. In such a representation features such as caves, grottos, tunnels, etc. are ignored. Such TIN models are widely used to represent topography and terrain in Geoinformatics and related fields, as unlike other available models (e.g. the regular grid model), they conveniently allow the consideration of rough surfaces and irregularly spaced elevation data [26], [27]. Note that the fineness of a TIN depends on the resolutions of the available geography data and hazard risk data and affects the computational expense of solutions. The higher the resolution of the data, the more vertices and edges the TIN has and therefore the finer the TIN is. As shown later in Section \textsection{V} for a TIN with a large number of vertices and edges, an exact approach may be computationally prohibitive and approximate approaches have to be invoked.

For each edge $e \in E$, we define a set of non-negative real number pairs $(h_l(e), g_l(e))$ (we call such number pair a tag), $l = 1, 2, \ldots, L$ on $e$, where $h_l(e)$ represents the laying cost, and $g_l(e)$ is the number of repairs (or failures) of the segment of a cable corresponding to edge $e$ if the protection level is $l$, and $L$ is the total number of available protection levels. Note that, because the resolution of the grid can be made sufficiently high, the edge length can be chosen sufficiently small so that each edge is homogenous; that is, all the points on the segment corresponding to an edge will have the same protection level. Without loss of generality, we assume the protection level variable $l$ is discrete and the total number of available protection levels $L$ is the same for each edge $e$. We let $h_{l_1}(e) \leq h_{l_2}(e)$ and $g_{l_1}(e) \geq g_{l_2}(e)$ if $l_1 < l_2$ for any $e \in E$, which implies that the higher the protection level, the higher the laying cost and the lower the repair rate. A path in the graph $G$ is a sequence of vertices without repetition and protection levels $(v_0, l_0, v_1, l_1, \ldots, v_{p-1}, l_{p-1}, v_p)$, such that for each of pairs $e_1 = (v_0, v_1), e_2 = (v_1, v_2), \ldots, e_p = (v_{p-1}, v_p)$ are edges of $G$, and $l_i, i = 0, \ldots, p-1$ is the protection level on edge $e_i = (v_i, v_{i+1})$. Let vertices $s, t \in V$ represent two points that to be connected by a cable, defined as a path $\gamma$ in $G$ that connects the two vertices. We use $\mathbb{H}(\gamma)$ and $\mathbb{G}(\gamma)$ to denote the laying cost and the (expected) total number of repairs (or failures) of the cable $\gamma$, respectively.

A. Laying cost model

The laying cost has several components such as material, labor, and licenses (e.g. right of way), and varies from one location to another. For $X = (x, y, z) \in \mathbb{D}$, we define a function $h(X, l)$ to represent the cable unit laying cost of protection level $l$ at location $(x, y, z)$, where $z = \xi(x, y)$. This function helps the path designer take into account laying cost variability for different locations and different protection levels. For an edge $e = (v, w) \in E$, a suitable approximation to its laying cost is

$$h_l(e) = \frac{h(X(v), l) + h(X(w), l)}{2} d(v, w), l = 1, \ldots, L, \quad (1)$$

where $X(v), X(w)$ are the coordinates of the vertices $v, w$, respectively, and $d(v, w) = d(e)$ is the length of the geodesic corresponding to the edge $e$. Then the laying cost of the cable $\gamma = (v_0, l_0, v_1, l_1, \ldots, v_{p-1}, l_{p-1}, v_p)$ is the sum of the laying costs on all edges along the path of the cable. That is,

$$\mathbb{H}(\gamma) = \sum_{i=0}^{p-1} h_{l_i}(e_i), \quad (2)$$

where $e_i = (v_i, v_{i+1})$.

Depending on the type of the cables, there are areas that cables may need to avoid or the cost required is extremely high. Setting appropriately high values to the function $h(X, l)$ will enable avoidance of such areas. In areas where the cost of the cable is only its length, we set $h(X, l)$ equal to a constant value, for instance, $h(X, l) = 1$.

B. Cable repair model

Inspired by [9], [10], [11] where repair rate and their correlation with ground movement are used to analyse seismic performance of pipelines, we use repair rate as a metric to
measure the effects of earthquakes on cables as well in this paper. As in [22], the number of potential repairs along a cable in the wake of earthquakes is used to serve as an index of the cost associated with the loss and reconstruction of the cable in the event of failure. In general, the larger the number of repairs, the larger the mean time to restore the cable. Next we discuss how ground movements resulting from earthquakes and protection level correlate with repair rate.

Repair rate is defined as the number of repairs per unit length of a cable. In general, it is a function of cable material and size (e.g. diameter), ground/soil conditions, and ground movement, for example, as measured by Peak Ground Velocity (PGV) and Permanent Ground Deformation (PGD) [8]. Apparently, for the same location X on the path of a cable, the probability of a repair event following an earthquake is lower if a higher protection level is adopted. Accordingly, along similar lines to the definition of laying cost, we define a function \( g(X, l) \) to represent the repair rate corresponding to protection levels \( l, l = 1, 2, \ldots, L \) at point \( (x, y, z) \in \mathcal{D} \), where \( z = \xi(x, y) \).

Many ground motion parameters have been used to establish a relationship between repair rate and seismic intensity [28]. In this paper, PGV is chosen to obtain the repair rate, because of the strong correlation between the two [29], [30], [31]. PGV is widely used in the literature for evaluating repair rates [8], [11], [28]. It is worth mentioning that the application of our method is not limited to PGV. Other ground motion intensity parameters can be used in place of PGV as an estimator of the repair rate. Evidently, the more precise the evaluation of the repair rate, the more reliable the path planning results.

After deriving the repair rate model at a point \( X \in \mathcal{D} \), for an edge \( e = (v, w) \in E \) corresponding to a segment of the cable, the number of repairs on \( e \) is approximated by

\[
g_l(e) = \frac{\bar{g}(X(v), l) + \bar{g}(X(w), l)}{2} d(v, w), \quad l = 1, \ldots, L, \tag{3}
\]

where \( X(v), X(w), \) and \( d(v, w) = d(e) \) are defined as before. Then the total number of repairs of the cable \( \gamma = (v_0, l_0, v_1, l_1, \ldots, v_{p-1}, l_{p-1}, v_p) \) is the sum of the repairs on each edge \( e_i = (v_i, v_{i+1}) \) along the path of the cable; that is,

\[
\mathcal{G}(\gamma) = \sum_{i=0}^{p-1} g_l(e_i). \tag{4}
\]

Note that the methodology in this paper is not limited to the laying cost model [1] and the cable repair model [3]. Alternative metrics in place of \( h_l(e) \) and \( g_l(e) \) can be used instead.

Based on the laying cost model and the repair rate model above, the multi-objective optimization problem in this paper is to minimize the laying cost and the total number of repairs; that is,

\[
\min_{\gamma} \left( \mathcal{H}(\gamma), \mathcal{G}(\gamma) \right), \tag{5}
\]

where \( \gamma \) is a path connecting the start vertex \( s \) and the destination vertex \( t \). In other words, the aim is to find the path that minimizes both the laying cost and total number of repairs of the cable. We note that if \( L = 1 \); that is, there is only one protection level, this problem can be mapped to be a multiple objective shortest path problem. However, for the case \( L > 1 \), to the best of our knowledge, this problem has not been studied before.

IV. Solutions

The two objectives considered in Problem (5), laying cost and total number of potential repairs, are in general conflicting. That is, to reduce the total number of repairs, we may need to make the path of the cable longer to avoid high risk areas, or adopt higher protection levels which will also increase the laying cost. It is therefore impossible to simultaneously optimize both the laying cost and the total number of repairs. In this situation, Pareto optimal solutions and related approaches are appropriate since different stakeholders have significantly different views of the cost of cable failures. A simple way to solve such multi-objective optimization problem is to build a new scalar function as the convex sum (i.e., with positive weights) of the two objectives. However, the weighted sum method is not considered here since it is not, in a general situation, able to derive non-convex portions of a Pareto front. In our context this means that non-convex portions of the Pareto front, if they exist, would be missed, and even the locations of possible non-convex portions would be unknown. In the following, to solve Problem (5), we will introduce a variant of the label setting algorithm which is an exact approach and is able to derive the complete Pareto front, and two approximate algorithms, an interval-partition-based label-setting algorithm and an evolutionary algorithm.

A. A label setting based exact algorithm

In essence, Problem (5) is a multi-objective shortest path problem. A common approach to solve multi-objective shortest path problems is the label setting method [13], an exact algorithm capable of finding all Pareto optimal solutions. Here we adapt the label setting algorithm [13] to handle the multi-objective shortest path problem (5), and exploit the stop condition proposed in [32] to avoid unnecessary computations. For an overview of multi-objective shortest path algorithms, see [33] and [34]. In the following, we describe the methodology employed here for path planning to solve Problem (5).

As for the label setting algorithm, our algorithm also applies to directed graphs. In fact, the first step is to convert the undirected graph in Section III to a directed graph, by replacing each edge by two oppositely directed edges and setting the same laying cost and number of repairs to each of those two directed edges. Note that since the laying cost and the number of repairs on each edge of the graph are non-negative, the conversion will does not introduce negative cycles; a key issue in applying the method.
For each vertex $v$, we will define a set of labels $Q_v$, each label consisting of a pair of values to represent aggregated laying cost and number of repairs, and denoted by $(\mathbb{H}, \mathbb{G})$. We stress that the label is defined on a vertex and the tag (as mentioned in Section 3) is defined on an edge. Each label on a particular vertex has a unique aggregated laying cost corresponding to a specific path from the source $s$ to this vertex, and any other label on the same vertex with higher aggregated laying cost must have a lower aggregated number of repairs. We use $M_i^k$ to represent the path from the source $s$ to the vertex $v$ and $k \in I_v$, where $I_v$ is the index set of labels on vertex $v$.

For example, as shown by Figure 1 let $v_1$ and $v_7$ be the source and destination, respectively. Assume that there are two protection levels, Level 1 and Level 2; that is, each edge has two tags, and the tag with higher laying cost but lower number of repairs corresponds to Level 2. It is straightforward to find several different paths from $v_1$ to $v_7$ and we can assign indexes to each of them. Assuming the third path $M_7^3 = (v_1, 2, 3, 1, v_5, 1, v_4, 2, v_6, 2, v_7)$; i.e., it passes through $v_1 \rightarrow v_3 \rightarrow v_5 \rightarrow v_4 \rightarrow v_6 \rightarrow v_7$ and the protection levels of corresponding edges of this path are 2, 1, 1, 2, and 2, respectively. The laying cost $\mathbb{H}_7^3 = 40$ and total number of repairs $\mathbb{G}_7^3 = 30$ are easily computed.

**Algorithm 1 Algorithm for Problem (5)**

**Input:** The graph $G = (V, E)$. The source vertex $s$ and the destination vertex $t$.

**Output:** All Pareto optimal paths from $s$ to $t$ on $G$.

1. **Initialization.** Set $Q_s = \{(0, 0)\}$, $I_s = \{1\}$ and $Q_v = \emptyset$, $I_v = \emptyset$, $v \in V \setminus \{s\}$. Let $T_v = \emptyset$, $v \in V$. Let $M_v^k = \{s\}$ for all $v \in V$ and $k \in I_v$.

2. If $\bigcup_{v \in V} (I_v \setminus T_v) = \emptyset$ then

3. **Stop.** Return label set $Q_t$ and corresponding paths on $t$.

4. else

5. Select $v \in V$ and $k \in I_v \setminus T_v$ so that $(\mathbb{H}_v^k, \mathbb{G}_v^k)$ is lexicographic minimal.

6. **end if**

7. for each arc $(v, w)$, $w \notin M_v^k$ do

8. $l = 1$. Let $n$ be the total existing labels on $w$.

9. while $l \leq L$ do

10. Let $\mathbb{H}' = \mathbb{H}_v^k + h_1(v, w)$ and $\mathbb{G}' = \mathbb{G}_v^k + g_1(v, w)$. 

11. if $(\mathbb{H}_v^k, \mathbb{G}_v^k)$ is not dominated by any label on $w$ and $l$ then

12. $n = n + 1$, $Q_w = Q_w \cup \{(\mathbb{H}_w^k, \mathbb{G}_w^k)\}$, $M_w^k = M_w^k \cup \{l, w\}$. Update $I_w$ accordingly.

13. for $k' = l \rightarrow n - 1$ do

14. if $(\mathbb{H}_w^{k'}, \mathbb{G}_w^{k'})$ is dominated by $(\mathbb{H}_w^k, \mathbb{G}_w^k)$ then

15. Delete $(\mathbb{H}_w^{k'}, \mathbb{G}_w^{k'})$ from $Q_w$ and the corresponding path $M_{w}^{k'}$. Update $I_w$ accordingly.

16. **end if**

17. **end for**

18. $l = l + 1$

19. **end if**

20. **end while**

21. **end for**

22. $T_v = T_v \cup \{k\}$

23. **Back to step 2.**

Here we use the simple example shown in Figure 1 to illustrate results obtained by Algorithm 1. We will provide two more complex examples in the next section. Note that our objective is to find Pareto optimal paths between the source $s$ and the destination $t$, there is no need to calculate all the labels on each vertex of the given graph. We set a stop condition (2) to avoid unnecessary computations. If a label is dominated by one of the existing labels of the destination $t$, it can never result in a Pareto optimal path and there is no need to consider additional labels spreading out from this label. The new label $(\mathbb{H}_w^k + h_1(v, w), \mathbb{G}_w^k + g_1(v, w))$ should not be dominated by any other existing labels on destination $t$. The process stops when all non-dominated labels have been treated. The complete details of this algorithm are shown by Algorithm 1. Note that in Algorithm 1 $T_v \subseteq I_v$ denotes the index set of labels on vertex $v$ which have been treated.

**Algorithm 1 Algorithm for Problem (5)**

**Input:** The graph $G = (V, E)$. The source vertex $s$ and the destination vertex $t$.

**Output:** All Pareto optimal paths from $s$ to $t$ on $G$.

1: Initialization. Set $Q_s = \{(0, 0)\}$, $I_s = \{1\}$ and $Q_v = \emptyset$, $I_v = \emptyset$, $v \in V \setminus \{s\}$. Let $T_v = \emptyset$, $v \in V$. Let $M_v^k = \{s\}$ for all $v \in V$ and $k \in I_v$.

2: If $\bigcup_{v \in V} (I_v \setminus T_v) = \emptyset$ then

3: **Stop.** Return label set $Q_t$ and corresponding paths on $t$.

4: else

5: Select $v \in V$ and $k \in I_v \setminus T_v$ so that $(\mathbb{H}_v^k, \mathbb{G}_v^k)$ is lexicographic minimal.

6: **end if**

7: for each arc $(v, w)$, $w \notin M_v^k$ do

8: $l = 1$. Let $n$ be the total existing labels on $w$.

9: while $l \leq L$ do

10: Let $\mathbb{H}' = \mathbb{H}_v^k + h_1(v, w)$ and $\mathbb{G}' = \mathbb{G}_v^k + g_1(v, w)$. 

11: if $(\mathbb{H}_v^k, \mathbb{G}_v^k)$ is not dominated by any label on $w$ and $l$ then

12: $n = n + 1$, $Q_w = Q_w \cup \{(\mathbb{H}_w^k, \mathbb{G}_w^k)\}$, $M_w^k = M_w^k \cup \{l, w\}$. Update $I_w$ accordingly.

13: for $k' = l \rightarrow n - 1$ do

14: if $(\mathbb{H}_w^{k'}, \mathbb{G}_w^{k'})$ is dominated by $(\mathbb{H}_w^k, \mathbb{G}_w^k)$ then

15: Delete $(\mathbb{H}_w^{k'}, \mathbb{G}_w^{k'})$ from $Q_w$ and the corresponding path $M_{w}^{k'}$. Update $I_w$ accordingly.

16: **end if**

17: **end for**

18: $l = l + 1$

19: **end if**

20: **end while**

21: **end for**

22: $T_v = T_v \cup \{k\}$

23: **Back to step 2.**
aggregated laying cost and total number of repairs of each Pareto optimal path are shown in Table I. From Figure 2 and Table I, we can observe the trade-off between the aggregated laying cost and aggregated total number of repairs. As can be seen, lower total number of repairs means much more investment in cable protection for the same path.

<table>
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<td>2, 2, 2</td>
</tr>
</tbody>
</table>

![Selected Pareto optimal paths for the example shown in Figure 1](image)

Since multi-objective shortest path problems are known to be NP-hard [35], so is Problem (5). Following the analysis in [36], the computational complexity of Algorithm I can be derived as

\[ O(DLT^2K^2\log(K)), \]

where \( D \) is the average graph degree, \( L \) is the total number of available protection levels, \( T \) is the number of objectives (\( T = 2 \) in this paper), and \( K \) is the total number of non-dominated labels of all vertices. For an application with very large number of non-dominated labels, Algorithm I will be computing-intensive. To accommodate this problem, we attempt and compare two approximation algorithms with limited computational cost. These are described below.

B. An interval-partition-based approximate algorithm

In this paper, the interval-partition-based label-setting approach (LS-IP) [37] which is a polynomial time approximation scheme with a performance guarantee is used to obtain the approximate Pareto front. Given any fixed \( \varepsilon > 0 \), the algorithm computes, in a time that is polynomial in the input size and \( \frac{1}{\varepsilon} \), a \((1+\varepsilon)\)-Pareto curve \( P_1 \). A \((1+\varepsilon)\)-Pareto curve \( P_2 \) is a finite set of feasible solutions such that each Pareto optimal solution \( \gamma \) is within a factor of \( (1+\varepsilon) \) of some \( \gamma' \in P_2 \) in all objectives. The main idea of the algorithm is to partition the label sets as arrays of polynomial size in order to avoid keep all non-dominated solutions, while producing an approximate Pareto set that can \((1+\varepsilon)\)-cover the Pareto optimal set. More details of the algorithm can be referred to [37], [38].

We adapt the LS-IP in [38] to solve Problem (5) approximately. To obtain a \((1+\varepsilon)\)-Pareto curve for a given \( \varepsilon \), the domain of the laying cost is partitioned into \( \lfloor \log_{(1+\varepsilon)\frac{\max}{\gamma}} n\max \rfloor + 1 \) intervals [38], where \( \max \) is the ratio of the maximum laying cost to the minimum laying cost on edges, \( n' \) is the number of edges of the feasible path with most edges and it is assumed to be equal to \( n-1 \) in [38], where \( n \) is the number of vertices of the graph \( G \). We note that, instead of assuming \( n' = n-1 \), we can let \( n' = \bar{n} - 1 \), where \( \bar{n} \) is the number of vertices on the non-dominated path \( \gamma \) with maximal laying cost (or minimal total number of repairs) since any other non-dominated path has fewer number of vertices than \( \gamma \). This path \( \gamma \) can be derived by running Dijkstra’s algorithm before running the LS-IP. In some cases, as shown in Section V, \( \bar{n} \) is much smaller than \( n \), resulting in far fewer intervals being required, as well as reducing the running time of the algorithm and therefore saving computational cost significantly. From [38], the computational complexity of the LS-IP is \( O(m\left(\frac{n\log(n\max)}{\varepsilon}\right)) \), where \( m \) is the number of edges in the graph \( G \).

C. An evolutionary algorithm

Evolutionary algorithms (EA) are a popular kind of heuristic search algorithm derived from the evolutionary process of genetic selection and variation. EAs use random and intelligent search to guide the search into the region of better performance in the search space. By the selection and variation process, a new set of individuals is created at each generation based on their fitness value. The breeding process borrowed from natural genetics make the evolution of populations have better performance for the environment than their predecessors. In this paper, we adopt an improved method based on SPEA (Strength Pareto Evolutionary Algorithm), namely SPEA2 [39], [40], since it is reported to have better performance on approximating Pareto set for multi-objective optimization problems compared with other strategies. Maria et al. [41] proposed a SPEA2 based evolutionary algorithm for multi-objective shortest path problem.

We adapt the algorithm, namely EA-SPEA2, in [41] to consider multiple protection levels. Because there are multiple levels for each edge, we randomly assign one of the protection levels to each initial path and offspring. More specifically, in the initialization stage, we use a random walk to generate a set of initial paths \( P \) between the given two sources \((s, t)\). We assume that \( \gamma \in P \) is one of initial paths composed of \( j \) edges, i.e. \( e_1, e_2, ..., e_j \). A protection level is uniformly randomly selected for each edge of \( \gamma \). In the variation stage, there are two kinds of variation operators, path mutation and path crossover. For the path mutation, a randomly selected vertex \( v \in \gamma \setminus \{s, t\} \) is mutated from path \( \gamma \). After removing the vertex \( v \) and inserting a new auxiliary vertex \( v' \), a new path \( \gamma' \) is created. Suppose that in the path \( \gamma \), the adjacent vertices of \( v \) are \( u_1 \) and \( u_2 \). For the new path \( \gamma' \), \( v' \) should be connected with nodes
$u_1$ and $u_2$ and the protection level of edge $e(u_1, u^*)$ and edge $e(u^*, u_2)$ need to be assigned uniformly randomly. For the path crossover operator, if a new path $γ^*$ is generated, only the connecting edge of two predecessors needs to be reassigned a protection level. The running time and performance of the EA-SPEA2 heavily depends on the population size and maximum number of generations. Using a larger population and a bigger maximum number of generations may make the generated non-dominated set approximate the Pareto front more accurate, and meanwhile will increase the computational cost accordingly. For more details on the algorithm, the reader can refer to [39], [40], [41].

V. APPLICATIONS AND NUMERICAL RESULTS

In this section, we provide three applications to illustrate and compare the three algorithms in Section IV. Firstly, in line with our previous work [22], we apply Algorithm 1 LS-IP and EA-SPEA2 to a 2D landform scenario, where the PGV data is simulated by running the PSHA method. Then, we apply these three algorithms to two 3D landform scenarios based on earthquake hazard estimation data from USGS. Without loss of generality, we assume there are two protection levels for both of these two scenarios. The aggregated laying cost and the aggregated total number of repairs of different cables are estimated and (approximate) Pareto fronts are generated. Note that the units of PGV and repair rate in this section are cm/s and number of repairs per km, respectively. We run the three algorithms coded in Matlab R2014b on a Dell OPTIPLEX 9020 computer (8 GB RAM, 3.6 GHz Intel(R) Core(TM) i7-4790 CPU).

A. Application to a 2D landform

We apply the three algorithms to a 2D example on a planar region as shown in Figure 3, where a 20 km long straight fault line, as a potential earthquake source, is assumed to be located in the region. The coordinates of the two end sites A and B of the fault line are [50 km, 40 km] and [50 km, 60 km], respectively. According to the bounded-Gutenberg-Richter model [12], without loss of generality, we assume earthquakes of magnitude from $m_{min} = 5$ to $m_{max} = 6.5$ are generated by this earthquake fault line source. Using the PGV data produced in our previous work. [22], and shown in Figure 3, we calculated the corresponding repair rate for each site $(x, y)$. Assuming there are two protection levels, Level 1 (low level) and Level 2 (high level), we calculate repair rates by the following equations.

\[ \bar{g}_1(x, y) = e^{1.30 \times \ln \bar{e}_{x,y} - 7.21}, \]  
\[ \bar{g}_2(x, y) = \frac{e^{1.30 \times \ln \bar{e}_{x,y} - 7.21}}{4.95}, \]

where $\bar{g}_l(x, y), l = 1, 2$ are the values of the repair rates on site $(x, y)$, and $\bar{e}_{x,y}$ is the mean PGV on site $(x, y)$. Note that Equation (6a) is the regression function of the repair rate on PGV derived in [11]. The resulted map for repair rates for Level 1 are shown in Figure 4.

Similarly, the laying cost functions for the two protection levels on each site $(x, y)$ are as follows,

\[ h_1(x, y) = 1, \]  
\[ h_2(x, y) = 2.22, \]

where $h_1(x, y)$ and $h_2(x, y)$ are costs on site $(x, y)$ for the low level and the high level, respectively. Note that $\bar{g}_2(x, y) < \bar{g}_1(x, y)$ and $h_2(x, y) > h_1(x, y)$. The assumption of Equations (6) and (7) is reasonable because spending more money on higher level protection design generally improves cable reliability. Note that in Equation (7b), without loss of generality, we let $h_2(x, y) = 2.22$ to verify the three algorithms. The reader can vary the value of $h_2(x, y)$ only if $h_2(x, y) > h_1(x, y)$. In practice, the repair rate and laying cost for different protection levels are estimated by designers according to specific project.

The objective is to lay a cable from the starting point (0 km, 50 km) to the destination (100 km, 50 km). To illustrate the gradual changes of the Pareto optimal paths (obtained by Algorithm 1) with decreasing minimum number of repairs, we select some of them shown in Figure 5 where white lines represent the path or path segments adopting Level 1 and the black lines represent the path or path segments adopting Level 2. The aggregated laying cost, $H$, and aggregated total number of repairs, $G$, of the selected Pareto optimal paths are shown in Table II where $H_1$ and $G_1$ represent the laying cost, and total number of repairs for the same paths in the case when all their segments have low protection level, that is, without any shielding protection. From Figures 5(a) 5(b) and 5(c) we...
can see that initially, providing protection for some parts of the cable in the high PGV region can significantly decrease the total number of repairs. As the total number of repairs decreases the optimal paths will avoid the high PGV region to decrease repairs though their length increases. Notice, for the different optimal paths, the alternative ways of reducing risk (reducing the number of repairs) by either adding segments with protection as the black lines in Figures 5(c) and 5(e) indicate, or by increasing the length of the cable and avoiding the high risk areas as shown in Figures 5(d) and 5(f). From Table II and Figure 5 we observe the trade-off between the aggregated laying cost and aggregated total number of repairs; that is, the smaller the total number of repairs, the greater is the laying cost.

**TABLE II:** Aggregated laying cost and total number of repairs of selected Pareto optimal paths (obtained by Algorithm 1) in the 2D example.

<table>
<thead>
<tr>
<th></th>
<th>H(γ∗)</th>
<th>G(γ∗)</th>
<th>H1(γ∗)</th>
<th>G1(γ∗)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>100.0000</td>
<td>1.0648</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>b</td>
<td>106.1199</td>
<td>0.9667</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>c</td>
<td>112.2398</td>
<td>0.8767</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>d</td>
<td>114.0833</td>
<td>0.8506</td>
<td>114.0833</td>
<td>0.8506</td>
</tr>
<tr>
<td>e</td>
<td>114.6878</td>
<td>0.8435</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>f</td>
<td>118.2254</td>
<td>0.7820</td>
<td>118.2254</td>
<td>0.7820</td>
</tr>
<tr>
<td>g</td>
<td>123.1960</td>
<td>0.7305</td>
<td>123.1960</td>
<td>0.7305</td>
</tr>
<tr>
<td>h</td>
<td>123.5915</td>
<td>0.7303</td>
<td>123.3675</td>
<td>0.7370</td>
</tr>
<tr>
<td>i</td>
<td>125.6812</td>
<td>0.7159</td>
<td>125.6812</td>
<td>0.7159</td>
</tr>
<tr>
<td>j</td>
<td>125.7036</td>
<td>0.7126</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>k</td>
<td>126.8679</td>
<td>0.7112</td>
<td>123.1960</td>
<td>0.7305</td>
</tr>
<tr>
<td>l</td>
<td>137.9434</td>
<td>0.5970</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>m</td>
<td>164.8709</td>
<td>0.4198</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>n</td>
<td>222.3980</td>
<td>0.2153</td>
<td>100.0000</td>
<td>1.0648</td>
</tr>
<tr>
<td>o</td>
<td>259.2461</td>
<td>0.1631</td>
<td>116.5685</td>
<td>0.8067</td>
</tr>
<tr>
<td>p</td>
<td>335.4937</td>
<td>0.1299</td>
<td>150.8528</td>
<td>0.6424</td>
</tr>
</tbody>
</table>

The black solid front in Figure 6 shows the complete Pareto front of this example obtained by Algorithm 1. This provides us with the results of the optimization problems of minimizing cable laying cost subject to a constraint on the total number of repairs (or equivalently, on the level of survivability) and minimizing the total number of repairs (or maximizing survivability) subject to a constraint on the cable laying cost.

We set, for LS-IP, ε = 0.8 and, for EA-SPEA2, the sizes of initial population, archive and the maximum number of generations to be 2500, 400, and 250, respectively. The approximate Pareto fronts of this example generated by the LS-IP and the EA-SPEA2 are shown as the blue dash front and magenta dot front in Figure 7, respectively. The total running time of each algorithm and the total number of solutions generated by them are shown in Table III. From Figure 7 we note that although theoretically the approximate Pareto front obtained by the LS-IP only achieves a [1, 8, 1]-cover of the Pareto optimal set, the online performance guarantee is substantially tighter. From Figure 6 and Table III it is seen that the LS-IP achieves a close approximation to Algorithm 1 with two fifths computational expense of the latter. However, even with more computational expense than that spent by Algorithm 1, the EA-SPEA2 failed to generate the solutions with large laying cost and small number of repairs although other parts of the approximate Pareto front are reasonable.

**TABLE III:** Running time and number of solutions of the three algorithms for the 2D example.

<table>
<thead>
<tr>
<th></th>
<th>Algorithm 1</th>
<th>LS-IP</th>
<th>EA-SPEA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running time(s)</td>
<td>55988</td>
<td>24339</td>
<td>50818</td>
</tr>
<tr>
<td>Solutions</td>
<td>339</td>
<td>234</td>
<td>400</td>
</tr>
</tbody>
</table>

**B. Application to a 3D landform**

We now apply the three algorithms to a 3D topographic landform. The ground motion intensity data is downloaded from USGS; this database is broadly recognized and applied in the seismic hazard field. The region of the hazard map is from a northwest point at (50.00°N, −125.00°E) to a southeast point at (24.60°N, −65.00°E) with 0.05 degree step in longitude and latitude. Our aim is to lay a cable in the region D, from (35.00°N, −118.00°E) to (33.00°N, −116.00°E) as shown by Figure 7(a). It is for a region in the State of California. Several fault lines cut through D, including the well known San Andreas fault line, indicated by a red line in Figure 7(a). The starting point and destination of the cable are at locations (33.55°N, −117.65°E) and (35.00°N, −116.00°E), respectively.

Calculation of the geodesic distance is based on the elevation data of the region D downloaded from the National Oceanic and Atmospheric Administration (NOAA). The sampling interval for the elevation data for every gridded point is 0.05 degree for both longitude and latitude. Using this elevation data, we obtain the elevation map of region D as shown in Figure 7(b).

The original ground motion data of this region in each gridded discrete point is Peak Ground Acceleration (PGA) (2%
Fig. 5: Selected Pareto optimal paths (obtained by Algorithm 1) in the 2D example. The white lines represent the path or path segments adopting low protection level (Level 1) and the black lines represent the path or path segments adopting high protection level (Level 2).

Fig. 7: Geography of Region D.

probability of exceedance in 50 years, $V_{s30} = 760$ m/s). One of our objectives is to calculate the total number of repairs of the designed path, which requires conversion of PGA to PGV. We use the transform equation from Wald [42] as follows,

$$
\log_{10}(v) = 1.0548 \cdot \log_{10}(PGA) - 1.5566,
$$

where $v$ is PGV. The shaded PGV map of the region $D$ is given in Figure 8. In this example, we also assume there are two protection levels, low level (Level 1) and high level (Level 2). The PGV data is used to calculate the corresponding values of the repair rate of each gridded point for the two protection levels using Equations (6a) and (6b). We use the same laying cost functions, Equations (7a) and (7b), to calculate the laying...
cost for levels 1 and 2, respectively.

Fig. 8: Logarithmic PGV map of the objective region $D$.

For convenience of calculation, the coordinates of geographic data and repair rate data are transformed from longitude and latitude to Universal Transverse Mercator coordinates. Combining the landform model introduced in Section III, the approximate graph representation of the landform is shown in Figure 10.

We observe from Figure 7(a) and Figure 8 that a cable from the start point to the destination must inevitably intersect the San Andreas fault line. Application of Algorithm 1 yields all Pareto optimal paths. As in the 2D example, we select some of them for illustration in Figure 10, with the corresponding laying cost and total number of repairs in Table IV. In Figure 10, each subfigure consists of a pair of figures including a 3D topographic landform figure on the left and the corresponding top view figure on the right providing a clearer illustration on the logarithmic PGV map, where magenta lines represent the path or path segments adopting Level 1 and the black lines represent the path or path segments adopting Level 2.

From Table IV and Figure 10, as in the 2D example, one observes the trade-off between laying cost and total number of repairs. From the first two subfigures, Figure 10(a) and Figure 10(b), it is clear that increasing the length of the path of the cable decreases the total number of repairs by avoiding some high PGV areas, but carrying with it a higher laying cost. However, reduction of the number of repairs by keeping the cable further away with the high PGV areas is not very effective. Deployment of a higher protection level for some segments of the cable is noticeable, and these segments become longer and more dense around the high PGV areas. By adoption of a higher protection level for the cable, the total number of repairs can decrease significantly but with an increased laying cost. As in the previous 2D example, we obtain the complete Pareto front of the 3D example shown by the black solid front in Figure 9.

Here we set $\varepsilon = 0.01$ for the LS-IP. For the EA-SPEA2, we let the sizes of initial population, archive and the maximum number of generations be 600, 300, and 250, respectively. The blue dash front and the magenta dot front in Figure 9 show the approximate Pareto fronts generated by the LS-IP and the EA-SPEA2, respectively. Table V lists the total running time and total number of solutions of each algorithm. As in the 2D example, the LS-IP achieves good approximation performance and has a very high effectiveness. The EA-SPEA2, which runs faster than Algorithm 1 but slower than the LS-IP, failed to generate the solutions with large laying cost and small number of repairs again.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>LS-IP</th>
<th>EA-SPEA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running time(s)</td>
<td>37928</td>
<td>1742</td>
</tr>
<tr>
<td>Solutions</td>
<td>1638</td>
<td>268</td>
</tr>
</tbody>
</table>
Fig. 10: Selected Pareto optimal paths (obtained by Algorithm 1) in the 3D example. The magenta lines represent the path or path segments adopting low protection level (Level 1) and the black lines represent the path or path segments adopting high protection level (Level 2).
Here, we consider a scenario with a large scale 3D landform, where a cable longer than one thousand kilometers is laid on the surface of the Earth. Algorithm 1 cannot be applied to such a scenario since there will be a huge number of non-dominated labels. The data is from the same source as the above 3D scenario of State of California. The region \( D' \) to be considered is in the central US and the New Madrid fault line, represented by the black lines in Figure 11, is located in the central of \( D' \). The logarithmic PGV map of region \( D' \) is shown by Figure 12. Our goal is to lay a cable from (33.00°N, −93.00°E) to (39.00°N, −87.00°E).

We adopt the two approaches to finding the approximate solution described earlier. For the LS-IP, we set \( \varepsilon = 0.8 \). For the EA-SPEA2, the sizes of the initial population and archive are 2500 and 400, respectively. And the maximum number of generations is set to be 250. The approximate Pareto fronts obtained by the two algorithms are shown by blue dash front (LS-IP) and magenta dot front (EA-SPEA2) in Figure 13. The running time of LS-IP and EA-SPEA2 are 39418s and 86022s, respectively. From Figure 13, it is seen that the EA-SPEA2 can not find the solutions on the two sides of the Pareto front if the generation or population size is not large enough. LS-IP performs much better than EA-SPEA2 since the former generates a better approximate Pareto front and runs faster comparing with the latter.

Based on all the above mentioned examples, we conclude that

- For Problem (5) with moderate size of non-dominated labels, Algorithm 1 is recommended since it is an exact algorithm which is able to obtain the complete optimal Pareto set.
- For Problem (5), where there are many non-dominated labels, our comparison of EA-SPEA2 and LS-IP leads us to conclude that the LS-IP approach should be adopted since it arrives at better solutions more efficiently.

VI. CONSIDERATION OF OTHER HAZARDOUS AND SENSITIVE AREAS

In addition to earthquakes, other natural hazards (e.g. landslides, debris flows, volcanoes, storms, hurricanes) and human activities (e.g. mining, fishing) may damage optical fiber cables. Most of these risk sources can be dealt with in the same way as earthquakes in the design of the path of a cable by the method proposed in this paper but it is necessary to have a model both for their laying costs and risks. We provide three examples as follows.

Landslides, caused by earthquakes or heavy rainfall, can break submarine telecommunication fiber cables. To evaluate the risk in an area due to landslides, geologists study the geology of the area (e.g. slope, aspect, soil, lithology etc.) and then create a landslide susceptibility map. With knowledge of trigger sources, such as earthquakes, and the susceptibility map, the amount and range of movement of landslides can be estimated, generating a landslides hazard map. Some work has been done in the field of civil engineering. Similarly, the landslides hazard map can be used to evaluate the potential destruction by landslides of cables for different cable protection levels.

Fig. 11: Geography of Region \( D' \). Source: Google Earth.

Fig. 12: Logarithmic PGV map of region \( D' \). Source: USGS.

Anchoring and fishing activities, especially bottom fishing, are the main causes of faults in submarine telecommunication fiber cables in shallow water. To reduce the risk of breakages of a cable, a steel wire “armor” can be added to the exterior together possibly with burial of the cable below the seabed...
if the cable passes through anchorage and fishery areas or, alternatively, the route of the cable can avoid such areas. To solve the problem of path planning and the non-homogenous construction of the cable taking into account such areas, we consider several protection levels; for example, lightweight cable (Level 1), single armored cable (Level 2), and double armored cable (Level 3). The laying cost of the cable at each location for the protection levels can be estimated from the price of each type of the cable, and the cost of labor and equipment. Also, for each protection level, the cable repair rate can be estimated from historical data of fishing activities and analyses of the mechanism of cable damage by fishing activities.

For areas that have to be avoided by the cable, such as areas those of high ecological value, or which are rocky or have military utility, the laying cost of each site in these areas can be set to be infinity.

VII. CONCLUSION

We have considered the path optimization and non-homogenous construction problem for a telecommunication cable connecting two points in high risk areas when multiple protection levels are available. Regarding laying cost and total number of repairs of the cable as the two objectives, we have formulated the problem as a multi-objective shortest path problem. We have modeled the Earth surface as a graph of TIN and evaluated the repair rate using ground motion intensity measures of earthquake events. The multi-objective shortest path problem has been solved using the label setting algorithm to obtain the Pareto front for the two objectives via numerous computer experiments. The Pareto front enables us to solve the following two single objective optimization problems.

1) Find the least-laying-cost cable and corresponding protection level for each segment of the cable subject to a constraint on the total number of repairs;
2) Find the cable with minimum total number of repairs and the protection level for each segment subject to a constraint on the total budget.

For the problem with a large number of non-dominated labels, the interval-partition-based label-setting algorithm can be used to obtain an approximate Pareto front in a reasonable running time. In future work, we will investigate algorithms that achieve good approximations more efficiently for large problems.

REFERENCES


