Path Planning of a New Undersea Telecommunications Cable with Consideration of Crossing Angle with Existing Cables

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ABSTRACT

Undersea telecommunication cables are critical components of the global infrastructure, with nearly every coastal nation connected via these "seabed highways." As of early 2025, there are over 600 active and planned undersea cables worldwide, spanning approximately 1.48 million kilometers and transmitting 99% of global internet traffic. Traditional manual path planning methods are inefficient and often result in suboptimal cable paths, making them difficult to account simultaneously for a range of natural factors and human activities that could impact cable cost and reliability. Notably, existing research overlooks planning guidelines recommended by the International Cable Protection Committee (ICPC), which emphasize minimization of proximity between new and existing cables. In this study, we introduce the ICPC-recommended cable crossing constraint into our previously developed automated route planning framework. Specifically, we adopt the Ordered Upwind Method to ensure that, when crossings are unavoidable, new cables intersect existing ones at an angle as close to 90° as possible. If a right-angle crossing is not feasible, a minimum angle of 45° is enforced. By incorporating this constraint into automated cable path planning, our approach aims to enhance the safety, maintainability, and long-term operability of both new and existing undersea cable systems.

Keywords: Undersea telecommunications cable, Ordered Upwind Method, cable crossing, path optimization

1. INTRODUCTION

Undersea optical fiber cables carry more than 99% of international voice and data communications, making them critical components of global information infrastructure. Planning optimal cable paths beneath oceans involves systematically determining efficient routes connecting designated points while simultaneously addressing a broad spectrum of geological and anthropogenic design considerations. These considerations typically include seismic hazards (such as earthquakes and volcanic activities), bathymetry, seabed gradients, sediment composition, protected marine habitats, and human-induced risks, including from fishing and anchoring activities [1]–[3].

The prevailing industry approach to undersea cable path planning relies heavily on manual adjustments, supplemented by dedicated software tools such as MakaiPlan [4]. MakaiPlan aids planners by computing initial shortest paths derived from the Great Circle method, but it lacks automated capabilities to optimize routes based on complex risk-cost assessments [4]. Consequently, extensive manual intervention remains necessary after preliminary calculations, so as to minimize risk exposure and control deployment costs.

Recent scholarly literature has introduced a variety of advanced analytical techniques and computational models to support undersea cable network optimization and resilience improvement. For instance, Neumayer *et al.* [5] proposed a network-based method to identify critical vulnerabilities and mitigate disaster-related network disruptions. Tran *et al.* [6] conducted seismic risk analyses on cable network infrastructure, recommending strategic enhancements within predefined budgetary constraints to bolster network robustness. Addressing multi-objective optimization explicitly, Wang *et al.* [7] formulated cable path planning as an Eikonal equation solvable via the Fast Marching Method (FMM) [8]. Unlike the standard Dijkstra algorithm for path planning in a network, FMM inherently accommodates continuous traversal beyond fixed grid boundaries, ensuring theoretically optimal paths over triangulated manifolds [1], [8]–[10]. The applicability and refinement of FMM-based optimization have been extensively investigated in subsequent research [11]–[16]. Recently, Wang *et al.* [11] introduced practical curvature constraints for undersea cable paths by systematically expanding restricted areas and replacing sharp directional transitions with smooth circular arcs, thereby improving both the applicability of the algorithm and the structural reliability of the resulting cable routes. Further practical enhancements were presented in [12], [13], where cable path planning strategies within complex trunk-and-branch topologies, explicitly incorporating latency constraints among network node pairs, were optimized.

Recognizing the impact of high-density data on automated cable route quality, Wang *et al.* [14] investigated the importance of detailed geospatial information for optimizing undersea cable paths. They identified key challenges in acquiring sufficiently dense datasets for high-resolution planning over multi-thousand-kilometer routes, as well as the scalability limits of algorithms processing such large volumes of data. To address these issues, Wang *et al.* [15] proposed methods based on parallel computing and multi-resolution analysis, improving both computational efficiency and routing quality. Building on this, they introduced the Adaptive Parallel FMM (APFMM) [16], which employs adaptive domain decomposition and dynamic resolution adjustment. Experimental results showed that APFMM outperformed conventional parallel FMM approaches, reducing runtime by over 81% in global-scale simulations exceeding 14,000 km.

Although the above studies have extensively investigated point-to-point cable path planning and cable system optimization, a significant aspect remains understudied: the crossing angles with existing cables while designing new cable paths. Existing cables include not only those currently in service but also obsolete or irreparably damaged cables still present on the seabed. According to guidelines issued by the International Cable Protection Committee (ICPC) [17], the path planning of new cables should, wherever feasible, avoid crossings with existing cables (particularly those currently in service) to prevent situations that could hinder repair operations on existing cable infrastructures. When cable crossings cannot be avoided, intersections are designed to be as close to 90° as possible, with a strictly enforced minimum angle of $45°$ if right-angle crossings are not achievable.

In this study, we use the Ordered Upwind Method (OUM) [18], which is an extension of FMM and suitable for anisotropic propagation scenarios, to explicitly incorporate cable crossing constraints into the cable planning process. Building on previous work by Wang *et al.* [19], who utilized OUM with seabed slope constraints, we use OUM to ensure crossing angles between new and existing cables follow ICPC guidelines.

2. CABLE PATH PLANNING TAKING ACCOUNT OF CROSSING ANGLES

2.1 Models

We represent the Earth's surface as a triangulated piecewise-linear two-dimensional manifold $\mathbb{M}$ embedded within a three-dimensional domain. Each point on the manifold $\mathbb{M}$ is assigned a three-dimensional coordinate (x, y, z), where x and y correspond to longitude and latitude, respectively, and $z = \xi(x, y)$ represents the elevation at that geographic location. More details can be found in [1], [2].

To assess the cost-effectiveness and long-term survivability of undersea cables comprehensively, we adopt a *life-cycle cost model* that incorporates multiple design considerations related to both natural and human activities that may potentially impact cable cost and reliability. Specifically, we consider a set of N design considerations, $N \in \mathbb{N}_+$, each of which is assigned a non-negative weight w_n, indicating its relative importance within the planning process, thus forming the set $W = \{w_1, w_2, ..., w_N\}$. Consequently, the life-cycle cost per unit length at a given point $\boldsymbol{x} \in \mathbb{M}$ is $C(\boldsymbol{x}) = \sum_{n=1}^{N} w_n c_n(\boldsymbol{x})$. Further elaboration can be found in [1], [2].

2.2 Cable crossing constraint

We define $\boldsymbol{d} : \mathbb{R}_+ \to \mathbb{D}$, where $\mathbb{D} = \{\boldsymbol{d} \in T_{\boldsymbol{x}}(\mathbb{M}) \mid \|\boldsymbol{d}\| = 1\}$, as the direction in which the OUM propagation advances. Here, $T_{\boldsymbol{x}}(\mathbb{M})$ denotes the tangent space of the manifold $\mathbb{M}$ at the point $\boldsymbol{x}$. This paper considers an existing cable path $\gamma_0 \subset \mathbb{M}$, consisting of a set of grid points on $\mathbb{M}$. Let $\boldsymbol{x}_1 = (x_1, y_1, z_1) \in \gamma_0$ and $\boldsymbol{x}_2 = (x_2, y_2, z_2) \in \gamma_0$ be the two grid points closest to a given grid point $\boldsymbol{x} = (x, y, z)$. If the direction of the cable path at $\boldsymbol{x}$ is given by $\boldsymbol{d}_{\boldsymbol{x}} = (\hat{x}, \hat{y}, \hat{z}) \in \mathbb{D}$, then the crossing angle $\theta_{\boldsymbol{x},\gamma_0}$ between the laying direction of the new cable at point $\boldsymbol{x}$ and the existing cable path γ_0 is defined as

$$\theta_{\boldsymbol{x},\gamma_0} = \cos^{-1}\left(\frac{|\langle \boldsymbol{d}_{\boldsymbol{x}}, \boldsymbol{v}\rangle|}{\|\boldsymbol{d}_{\boldsymbol{x}}\| \cdot \|\boldsymbol{v}\|}\right), \tag{1}$$

where $\boldsymbol{v} = \boldsymbol{x}_1 - \boldsymbol{x}_2$. Note that we compute the smaller intersection angle by taking the absolute value $|\langle \boldsymbol{d}, \boldsymbol{v}\rangle|$, ensuring that $\theta_{\boldsymbol{x},\gamma_0} \in [0°, 90°]$. Let $\Phi(\boldsymbol{x}, \theta_{\boldsymbol{x},\gamma_0})$ denote the penalty cost associated with an intersection with the existing cable γ_0. To align with the ICPC recommendations for acceptable crossing angles [17], we model the penalty cost per unit length at a given point $\boldsymbol{x} = (x, y, z) \in \mathbb{M}$ as the following exponential function:

$$\Phi(\boldsymbol{x}, \theta_{\boldsymbol{x},\gamma_0}) = \frac{k \cdot (e^{0.1(90° - \theta_{\boldsymbol{x},\gamma_0})} - 1)}{e^{4.5} - 1}, \tag{2}$$

where k is an adjustable parameter set by planners according to practical requirements. Equation (2) ensures that the penalty is minimized when the crossing angle is 90° and increases exponentially as the angle decreases, particularly when it falls below $45°$ - a condition that is largely avoided in practice.

2.3 Problem formulation

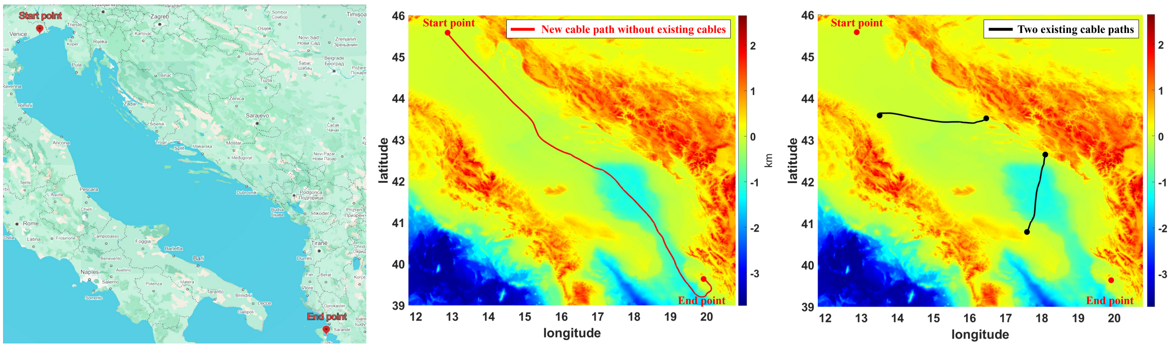
The goal is to identify an optimal new undersea cable path γ^* between two designated points A and B with minimal total life-cycle cost, while taking account of the crossing constraint at each of P crossings with existing cable, forming the set $\Omega = \{\gamma_1, \gamma_2, ..., \gamma_P\}$, where $P \in \mathbb{N}_+$. The corresponding objective function is:

$$\min_{\gamma^*} \mathbb{C}\left(\gamma^*\right) = \min \int_{l(0)}^{l(\gamma^*)} C\left(\boldsymbol{x}\left(s\right)\right) + \sum_{p=1}^{P} \Phi(\boldsymbol{x}\left(\boldsymbol{s}\right), \theta_{\boldsymbol{x},\gamma_p}))ds, \qquad \textit{s.t. } \gamma^*(0) = A, \gamma^*(l) = B, \tag{3}$$

where $l(\gamma^*)$ denotes the total length of the new cable path γ^*. Equation (3) can be transformed into a nonlinear partial differential equation with anisotropic characteristics (namely, the anisotropic Eikonal equation), and this can be solved efficiently using the OUM. Further methodological details are provided in [19].

3. APPLICATION

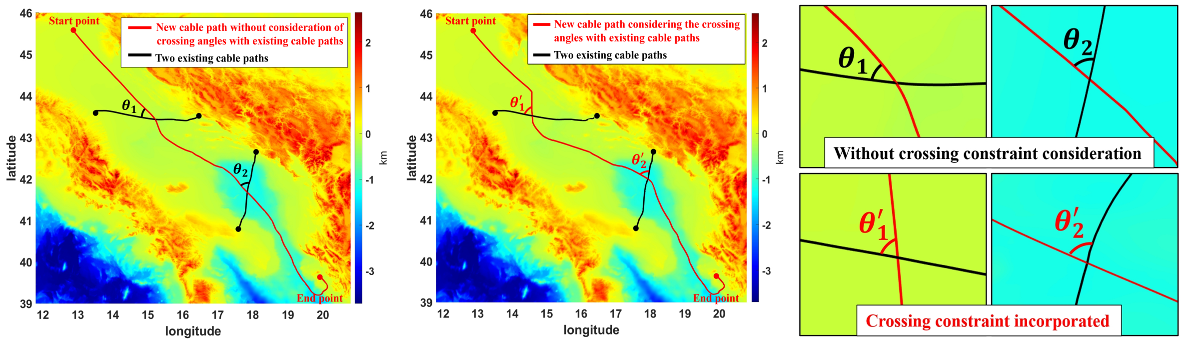
Here we demonstrate the path planning of a new undersea cable connecting a start point $(45°34'42''\text{N}, 12°52'23''\text{E})$ in the Metropolitan City of Venice, Italy, to an end point $(39°37'59''\text{N}, 19°55'00''\text{E})$ in Corfu, Greece, highlighted by red pins in Fig. 1(a). For comprehensive details on the design issues, their calculation methodology, and the associated weighting factors, we refer to [2].



(a) Target area.

(b) New cable path planning without existing cables.

(c) Two existing cable paths in target area.



(d) New cable path planning without accounting for crossing angles constraints.

(e) New cable path planning taking account of crossing angles constraints.

(f) Partial enlarged view of the crossing angle variation.

Figure 1: Undersea cable path planning with crossing angle constraints relative to existing cable paths.

TABLE I: Numerical results of the new undersea cable paths in Fig. 1.

	The new cable path in Fig. 1(d)	The new cable path in Fig. 1(e)	Crossing angles in Fig. 1(f)
Length (km)	1000.419	1062.739	θ_1 = 41.37°, θ_2 = 64.15°
Life-cycle cost (million \$)	28.036	29.854	θ'_1 = 74.19°, θ'_2 = 81.26°

Fig. 1(b) shows the optimal new undersea cable path (red line) obtained by OUM without any existing cables in the target area. In Fig. 1(c), two existing cable paths are introduced (black lines). As illustrated in Fig. 1(d), if these existing cables are not considered during the planning process, the new cable may intersect them at angles smaller than 45°, which violates the ICPC guidelines. Such small crossing angles can hinder future maintenance of the existing infrastructure. Fig. 1(e) presents the optimized path generated using OUM with cable crossing constraints. Compared to Fig. 1(d), both the crossing angles θ_1 and θ_2 are significantly increased — a difference more clearly visible in the magnified view in Fig. 1(f). Table I summarizes the numerical results of cable paths with and without crossing angle constraints in Fig. 1. While incorporating these constraints results in some increase in total cable length and life-cycle cost (by only 6.22% and 6.48%, respectively), this is a reasonable trade-off. As the typical lifespan of undersea cable systems is 25 years, ensuring adequate crossing angles is crucial for the maintenance of long-term accessibility and serviceability of existing cables.

4. CONCLUSION

We have incorporated cable crossing constraints recommended by ICPC into our automated undersea cable path planning framework using OUM. Our method ensures that new cable paths intersect existing cables at angles as close to 90° as possible, strictly enforcing a minimum crossing angle of 45° when right-angle intersections are unattainable. Numerical results have demonstrated that the integration of these constraints resulted in only moderate increases (approximately 6%) in total cable length and life-cycle cost, representing an acceptable compromise. This approach guarantees suitable crossing angles, thereby enhancing long-term accessibility and maintainability of both existing and newly deployed cables, and significantly improves the reliability of undersea telecommunications cable networks by addressing a previously overlooked yet critical aspect of infrastructure planning.

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