二、主要研究成果與重大突破（請分別敘述各子計畫成果，並請敘明頂尖論文與會議之認定標準與簡要介紹）

Subproject 3

In this project, we study the routing problem via LEO satellite constellation. Specifically, we consider the extensive communication range of laser inter-satellite link (LISL) and the significant computational overhead of enormous number of satellites. To cope with such challenges, we propose a bidirectional search algorithm called DBS, which can efficiently search the routing path with reduced search space.

Also, three variants of DBS algorithms are designed to meet different requirements. First, DBS-OP is for finding an optimal solution. It can achieve the least cost path routing with lower computational complexity. Second, DBS-FS is tailored for scenarios requiring fast routing, which prioritizes reducing the search space on multi-layer topologies to enhance routing efficiency. Finally, we consider the potential disruption in LEO satellite networks, such as node failures or battery depletion. To ensure data delivery in such conditions, DBS-RC is designed to offer a resilient yet efficient path reconstruction routing.

The proposed DBS algorithms can find the satellite routing solution efficiently in various LEO satellite constellation settings. We found that DBS-OP demonstrates superior performance when the constellation size expands significantly, and shows increasing efficiency as satellite nodes become denser. Moreover, DBS-FS can prune the search space effectively, due to its termination condition. DBS-FS is up to four times faster than DBS-OP, and its advantage over traditional routing algorithms is more pronounced. Finally, unlike other traditional routing algorithms, which must reconstruct the entire path to restore availability, DBS-RC can quickly adapt to changes. The reconstruction performance is shown in the figure. This helps to minimize performance degradation caused by frequent or numerous node failures. To sum up, our proposed solution enhances pathfinding efficiency in multi-layer LEO satellite mega-constellations utilizing LISL technology. It demonstrates a vision to provide efficient routing capabilities for future LISL-enabled LEO mega-constellations.

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Figure 1. Orbital Parameter

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Figure 2. Battery-drained node ratio vs. path reconstruction time

comparison

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Figure 3. Search space comparison in the real-world scenario

研究成果（本資料將公開於網站上）

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※本成果請提供中文及英文。

[子計畫3]

在本計畫中，我們研究了透過低軌道衛星星座進行路徑搜尋的問題。我們考慮了雷射星際鏈路（LISL）廣泛的通信範圍以及大量衛星帶來的顯著計算成本。因此我們提出名為 DBS 的雙向搜尋演算法，該演算法能夠在減少搜尋空間的情況下，高效地搜尋路由路徑。此外，我們設計了三種 DBS 演算法的變體，以滿足不同的需求。首先，DBS-OP可以在較低的計算複雜度下實現最低成本的路徑搜尋。其次，DBS-FS 針對需要快速路由的場景，可在多層拓撲結構中縮小搜尋空間，以提高搜尋效率。最後，DBS-RC考慮了低軌道衛星網路中可能發生的中斷，例如節點故障或電池耗盡。其能夠在保持效率的同時，提供具備恢復能力的路徑重建方案。

我們提出的 DBS 演算法能夠在各種低軌道衛星星座環境下，高效地找到衛星最佳路徑。我們發現，當星座規模顯著擴大時，DBS-OP 展現出卓越的性能，且隨著衛星節點密度增加，其效率亦隨之提升。此外，由於 DBS-FS 的終止條件，因此可以有效地修剪搜尋空間，其運行速度最高可達 DBS-OP 的四倍，其優勢相較傳統演算法更加明顯。最後， DBS-RC 無需重新構建整條路徑來恢復可用性，而是能夠迅速適應變化，有助於減少因頻繁或大規模節點故障導致的性能下降。

總結而言，我們提出的解決方案提高了多層低軌道衛星巨型星座在 LISL 技術下的路徑搜尋效率，展現了對於未來LISL低軌道巨型星座提供高效路由能力的願景。

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