

A large-scale LEO satellite network topology generation method based on physical-logical semantic decoupling

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The generation of Low Earth Orbit (LEO) satellite network topology is fundamental to inter-satellite communication and space computing. Existing methods generally construct topologies based on instantaneous geometric constraints and fixed thresholds, which may cause frequent temporal fluctuations in network topology and fail to satisfy structural continuity requirements of space computing scenarios. To address this issue, this paper proposes a large-scale LEO satellite network topology generation method based on physical-logical semantic decoupling. First, orbital planes are identified through regular Right Ascension of Ascending Node (RAAN) lattices' assignment. Then, a two-phase topology generation strategy is introduced to reconstruct the regular topology structure. By explicitly decoupling the physical and logical semantics of links, the proposed method generates two topology representations: a strict mode containing only physically feasible links and a hybrid mode integrating logical links for structural continuity, corresponding to real-time communication and space computing applications, respectively. Experimental results demonstrate that the proposed method significantly improves temporal stability and structural integrity compared with K-Nearest Neighbour (KNN) and geometry-aware grid baselines while maintaining physical feasibility. Compared with the strict mode, the hybrid mode achieves better structural continuity, connectivity, and downstream task suitability, providing a more stable topology foundation for task scheduling, federated learning, and dynamic graph learning in space computing networks.

Keywords – Dynamic graphs, inter-satellite networks, network stability, space computing, topology generation

1. INTRODUCTION

With the continuous expansion of large-scale Low Earth Orbit (LEO) satellite constellations such as Starlink and the increasing diversity of application scenarios, LEO satellites have evolved from traditional communication infrastructures into computational carriers of distributed space computing and space intelligence [1]. Driven by the improvements in onboard processing capabilities, LEO satellite networks are increasingly capable of supporting space intelligent applications such as task scheduling, federated learning and multi-satellite collaborative inference. As network topology directly determines data transmission scope, resource coordination paths and task propagation efficiency, constructing a topology that simultaneously preserves physical feasibility and structural continuity has become a fundamental research problem in space computing networks.

For space computing and space intelligence applications, satellite network topology is not only used as a communication structure but also serves as input to graph-based learning models or as supervisory signals. This necessitates that the topology exhibits temporal continuity and evolutionary stability, thereby providing a continuous and stable topological foundation for space task scheduling, multi-satellite cooperation and dynamic graph learning. Accordingly, topology in space computing networks should not only reflect instantaneous physical feasibility but also preserve continuous structural adjacency throughout orbital evolution.

These two objectives correspond to different types of constraints. Physical feasibility is a local constraint determined by instantaneous orbital geometry, whereas structural continuity reflects a global temporal consistency constraint across time steps. Existing LEO satellite network topology generation methods are predominantly based on instantaneous geometric relationships and fixed physical thresholds [2][3][4], treating topology evolution as an instantaneous response to geometric states. While such methods can capture instantaneous communication reachability,

they neglect temporal structural continuity constraints. As a result, topology evolution is entirely driven by instantaneous states, and links near geometric threshold boundaries tend to change frequently between adjacent time steps, thereby amplifying orbital perturbations into structural fluctuations. In particular, for applications such as dynamic graph learning and topology prediction, such instability further leads to adjacency drift and frequent routing reconfiguration.

In addition, different types of Inter-Satellite Links (ISLs) in LEO satellite networks exhibit distinct structural roles and dynamic characteristics. For example, intra-plane links are relatively stable due to consistent orbital relationships and are therefore better suited for maintaining the network backbone, whereas inter-plane links are more dynamic due to orbital plane differences and relative motion, primarily supporting cross-plane communication [2]. However, existing methods typically apply unified physical constraint models to all link types, failing to capture their distinct structural roles within the network and making it difficult to simultaneously maintain physical feasibility and structural continuity.

Therefore, constructing a dynamic topology that simultaneously preserves physical feasibility and structural continuity remains a critical challenge in space computing networks. To address this issue, this paper proposes a large-scale LEO satellite network topology generation method based on physical-logical semantic decoupling. By separately modelling the physical and logical semantics of links, the proposed method enables continuous topology representation for dynamic scenarios. In particular, physical semantics describe whether a link satisfies physical feasibility constraints, while logical semantics preserve continuous structural adjacency relationships across time.

The main contributions of this paper are summarized as follows: 1) A dual-semantic topology generation method for large-scale LEO satellite networks is proposed, which decouples the physical and logical semantics of dynamic satellite networks and enables joint modelling of instantaneous physical feasibility and structural continuity. 2) A regular RAAN lattice-based orbital plane identification mechanism is proposed, which transforms the orbital plane partition problem from an unconstrained clustering problem into a one-dimensional alignment problem, thereby providing more balanced structural inputs for subsequent link construction. 3) A structured two-stage topology construction strategy is designed. In Phase 1, the Walker constellation backbone structure is recovered through explicit "2+2" slot-based link construction. In Phase 2, hierarchical link supplementation is performed to repair local connectivity defects while preserving the semantic structure. 4) A dual-semantic link representation mechanism is proposed to enable differentiated modelling of inter-satellite links with distinct functional roles. Based on this mechanism, two topology output modes, namely strict and hybrid, are constructed to represent physical communication networks and structurally continuous networks, respectively, supporting the requirements of different space computing tasks.

2. RELATED WORK

Existing topology construction methods for LEO satellite networks primarily revolve around physical constraints and structural priors. Methods based on physical constraints establish topology satisfying physical communication constraints by enforcing conditions such as inter-satellite distance, earth occlusion and minimum elevation angle [5], offering strong physical interpretability. Methods based on structural priors rely on predefined constellation rules or design assumptions, such as the +Grid connection pattern [6], repeated local motifs [7] or K-Nearest Neighbour (KNN) graphs [8], to reduce construction and maintenance complexity. Building upon these, some studies further combine physical constraints with structural design to improve network performance through link assignment optimization [9] or demand-aware strategies [10].

However, most existing methods still establish links based on instantaneous geometric states and fixed thresholds in a discrete manner, causing links near geometric threshold boundaries to switch frequently between adjacent time steps and thereby undermining the structural continuity of the topology. In addition, structural methods often ignore physical feasibility and may generate infeasible links, while hybrid methods still primarily focus on communication performance optimization. Essentially, these approaches treat topology evolution as a discrete response to instantaneous physical states, lacking explicit modelling of dynamic structural continuity and thereby failing to simultaneously preserve physical feasibility and structural continuity.

With the development of Graph Neural Networks (GNNs) and spatio-temporal modelling techniques, data-driven dynamic graph learning methods have been widely applied in satellite network research. Existing studies typically learn temporal evolution patterns of network structures based on pre-constructed topology sequences and associated state information [11], and aim to predict future links or graph changes to assist routing optimization, resource scheduling and collaborative task execution. Some work enhances the characterization of dynamics through virtual topology methods [12], virtual node methods [13] or Finite State Automata (FSA) [14].

However, these methods typically assume that the input topology serves as stable and reliable supervisory signals, without a unified modelling of topology evolution and structural continuity. Since topology established based on instantaneous physical thresholds is prone to temporal structural fluctuations, such discontinuities can be directly propagated into the dynamic graph learning process, leading to adjacency drift, label noise and semantic inconsistency. In addition, existing approaches commonly lack differentiated modelling of the structural roles and dynamic characteristics of different link types, which further limits the ability of models to capture temporal structural evolution patterns.

With the development of space computing and space intelligence, LEO satellite networks are evolving from communication infrastructures into key platforms supporting task execution, resource orchestration and distributed

collaborative computing. Recent studies have begun to explore the role of network topology in intelligent tasks, attempting to improve system performance through joint modelling of network topology [15] or by incorporating structural priors and temporal continuity constraints. In scenarios such as resource scheduling, federated learning and multi-satellite collaborative inference, network topology not only determines physical feasibility but also influences task migration paths, collaboration scopes and computational organization patterns. For instance, computing task scheduling commonly relies on network structure to determine task transmission paths [16]; federated learning depends on relatively stable communication adjacency to ensure efficient model aggregation [17]; and distributed onboard inference similarly requires collaboration topology with temporal continuity [18].

Nevertheless, these approaches generally treat topology as a static and predefined input, lacking unified modelling of the topology generation process and structural continuity. Consequently, structural fluctuations caused by instantaneous physical states must be passively handled by upper-layer task mechanisms, increasing the complexity of system scheduling and collaborative optimization. Furthermore, existing methods have not established a unified modelling framework that jointly considers physical feasibility, structural continuity and topological semantic representation, making it difficult to provide dynamic topology that is structurally continuous, interpretable and suitable for graph learning in space computing scenarios.

3. SYSTEM MODEL AND PROBLEM FORMULATION

3.1 Constellation system model

This paper considers the Starlink constellation at 550 km altitude and 53° inclination as the case study, which follows a Walker configuration with 72 orbital planes and 22 satellites per plane (1584 satellites in total). The satellites operate in near-circular orbits with an orbital period of approximately 95.5 minutes.

At time t , the satellite network can be represented as a dynamic undirected graph:

$$G(t) = (V, E(t), \mathbf{X}(t)) \quad (1)$$

where V denotes the satellite node set, $E(t) \subseteq V \times V$ represents the set of ISLs established at time t , and $\mathbf{X}(t)$ denotes the node state feature matrix. The state vector of any satellite node $v \in V$ at time t is defined as:

$$x_v(t) = [p_v(t), v_v(t), \theta_v(t)] \quad (2)$$

where $p_v(t)$ denotes the satellite position in the Earth-Centered Earth-Fixed (ECEF) coordinate system, $v_v(t)$ is the velocity vector. The orbital parameters set $\theta_v(t)$ includes inclination i_v , RAAN Ω_v , mean anomaly M_v , and the latitude ϕ_v , and longitude λ_v of the sub-satellite.

For temporal discretization, a fixed time step Δt is adopted to generate topologies for N consecutive time frames, thereby producing a time-varying topology sequence spanning multiple orbital periods and fully capturing the dynamic evolution characteristics of the constellation topology during continuous orbital motion.

3.2 ISL constraint model

To ensure that the generated topology has clear engineering significance, this paper defines the following constraints for ISL.

Constraint 1: Distance constraint. An ISL can be established only if the distance between two satellites does not exceed a maximum threshold d_{max} :

$$d_{uv}(t) = \|r_u(t) - r_v(t)\|_2 \leq d_{max} \quad (3)$$

Based on the nominal intra-plane spacing $\frac{2\pi R_0}{N_s} = \frac{2\pi \times (6371 + 550)}{22} \approx 1976.6$ km in the Starlink 550 km / 53°

constellation shell, a 10% engineering margin is applied, resulting in a threshold of $d_{max} = 2175$ km.

Constraint 2: Earth occlusion constraint. An ISL can be established if the line segment between two satellites does not pass through the Earth. Let the position vectors of satellites U and V be $\mathbf{r}_u$ and $\mathbf{r}_v$, respectively. The link is considered unobstructed if the distance from the midpoint of the line segment connecting them to the Earth's center exceeds the Earth's radius R_E :

$$\text{vis}(u, v, t) = \begin{cases} 1, & \min_{s \in [0, 1]} \|\mathbf{r}_u + s(\mathbf{r}_v - \mathbf{r}_u)\|_2 > R_E \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

Constraint 3: Degree constraint. The target number of links per satellite is constrained to 4, following the "2+2" structural constraint:

$$\deg(v) \leq k_{max} = 4, \quad \forall v \in V \quad (5)$$

3.3 Dual-semantic topology model

3.3.1 Dual-semantic link representation

In large-scale LEO constellation networks, ISL construction faces a trade-off between physical feasibility and structural continuity. Relying solely on physical constraints may lead to topological fragmentation, whereas rule-based structural construction may introduce physically infeasible links. To address this issue, a dual-semantic link representation mechanism is proposed to explicitly partition the ISL edge set based on physical feasibility and structural continuity.

During orbital evolution, links that satisfy the distance threshold and are free from Earth occlusion are defined as the physically feasible link set $E_{phys}(t)$:

$$E_{phys}(t) = \{(u, v) \mid d_{uv}(t) \leq d_{max}, \text{vis}(u, v, t) = 1\} \quad (6)$$

During orbital evolution, intra-plane links that maintain stable adjacency relationships but temporarily violate strict physical distance threshold due to instantaneous geometric variations, while remaining free from Earth occlusion, are defined as logical link set $E_{logic}(t)$:

$$E_{logic}(t) = \{(u, v) \mid \pi(u) = \pi(v), d_{uv}(t) > d_{max}, vis(u, v, t) = 1\} \quad (7)$$

where $\pi(u) \in \{0, 1, \dots, N_{plane} - 1\}$ denotes the orbital plane index of satellite u , determined by the regular RAAN lattice algorithm in Section 4.2. Logical links are used to preserve structural continuity of intra-plane topology during dynamic orbital evolution. All inter-plane links strictly maintain physical constraints throughout the generation process.

Based on the above distinction, two topology generation modes, namely a strict mode and a hybrid mode, are further defined to represent physically executable communication networks and structurally continuous topologies, respectively. Together, they form the proposed topology modelling framework.

3.3.2 Definition of strict/hybrid dual-mode topologies

Based on the dual-semantic link distinction introduced in Section 3.3.1, this paper first defines the physically constrained topology generated according to inter-satellite communication constraints as the strict mode topology. Subsequently, by further incorporating logical semantic information, a structurally continuous topology is constructed and defined as the hybrid mode.

Strict mode topology $G_{strict}(t)$: contains only physically feasible links, with edge set satisfying:

$$E_S(t) \subseteq E_{phys}(t), \quad \deg(v) \leq 4, \quad \forall v \in V \quad (8)$$

In this mode, all links in the topology satisfy physical constraints and therefore represent physically realizable communication states, making the topology suitable for scenarios such as real-time data transmission for on-orbit computing tasks and latency-sensitive routing.

Hybrid mode topology $G_{hybrid}(t)$: superimposes intra-plane logical links onto the physically feasible links, with edge set that satisfies:

$$E_H(t) \subseteq E_{phys}(t) \cup E_{logic}(t), \quad \deg(v) \leq 4, \quad \forall v \in V \quad (9)$$

In this mode, the topology contains two semantically different types of links. Links in $E_{phys}(t)$ can be directly executed at the physical layer, while links in $E_{logic}(t)$ are used to describe continuous structural adjacency relationships and service-layer network organization during continuous orbital evolution, without participating in actual physical data transmission. By introducing structural links, the hybrid mode preserves structural continuity under dynamic geometric variations, thereby forming a structurally

continuous topology for space computing tasks rather than merely a connectivity graph reflecting instantaneous physical communication capabilities.

The two modes correspond to two fundamentally different forms of network: physically executable communication network and structurally continuous topology. They are designed to distinguish actual communication capability from structural continuity of the topology. A comparison of their key properties and application scenarios is provided in Table 3-1.

Table 3-1 – Comparison of two topology generation modes

Attribute	Strict Mode	Hybrid Mode
Edge Set	$E_{phys}(t)$	$E_{phys}(t) \cup E_{logic}(t)$
Physical Feasibility	All links guaranteed	Partially guaranteed only
Intra-Plane Ring Continuity	Not guaranteed	Guaranteed (logical layer)
Average Node Degree	≤ 4	≤ 4
Typical Applications	Real-time data transmission, latency-sensitive routing, computing result backhaul	Federated learning communication graph, on-orbit computing task scheduling planning, control-plane network awareness

3.4 Problem formulation

Based on the above model and definitions, the core problem of this paper can be summarized as follows: given real orbital state sequences, how to jointly satisfy physical feasibility and structural continuity while performing differentiated modelling for different links, consequently generating dynamic topology sequences with structural integrity and temporal stability.

Let the input be the satellite state sequence driven by real Two-Line Element (TLE) data $X = \{X_1, X_2, \dots, X_T\}$. The objective is to solve for the mapping from the state sequence to the topology sequence:

$$F : X \rightarrow G = \{G_1, G_2, \dots, G_T\} \quad (10)$$

The edge set of the topology $G(t)$ at any time t should not only satisfy link feasibility and node degree constraints, but also achieve coordinated optimization in terms of network connectivity, structural regularity, and temporal structural continuity:

$$\min L(G_t) = \lambda_1 L_{conn} + \lambda_2 L_{struct} + \lambda_3 L_{temp} \quad (11)$$

where L_{conn} denotes the connectivity loss, which measures the proportion of isolated nodes; L_{struct} denotes the structural consistency loss, which constrains the degree distribution to approximate the target topological structure; and L_{temp} denotes the temporal stability loss, which constrains topological changes between adjacent time steps.

These three optimization objectives are not independently defined but instead originate from the common requirements of space communication networks and space computing networks for underlying topology. Network connectivity ensures global task execution and data exchange, serving as a fundamental prerequisite for distributed onboard task scheduling and cross-node collaborative computing. Structural regularity ensures the predictability of network organization, thereby providing stable structural support for routing planning, task scheduling and graph learning models. Temporal structural continuity is proposed to reduce reconstruction overhead caused by abrupt topological changes between adjacent time steps, thus improving control stability and task execution efficiency in dynamic satellite networks.

Therefore, rather than focusing on generating an optimal link set for a single snapshot, this paper aims to construct dynamic topology sequences that jointly consider physical feasibility, structural regularity and temporal stability, thus providing a unified topological foundation for downstream applications such as routing, scheduling and space computing collaboration.

4. DUAL-SEMANTIC TOPOLOGY GENERATION METHOD

4.1 Overall framework

Based on the system model and problem formulation in Section 3, this paper proposes a dual-semantic topology generation method for large-scale LEO satellite networks to address issues of insufficient connectivity, poor structural continuity and severe topology instability in dynamic topology modelling. The proposed method decouples physical semantics and logical semantics, preserving structural continuity while satisfying physical constraints, thereby generating stable dynamic topology.

Specifically, the overall workflow of the proposed method is as follows. Given satellite TLE data, shell-layer filtering and orbital propagation are first performed to obtain the satellite state sequences. Subsequently, regular RAAN lattice assignment and slot mapping are executed to complete orbital plane structure partitioning and seam plane detection. Then, a two-phase topology generation strategy is performed. In Phase 1, structured link construction is conducted based on the "2+2" slot mechanism to generate the topology backbone. In Phase 2, a hierarchical link supplementation mechanism is applied to repair local structural defects. During the link generation process, each link is simultaneously assigned physical feasibility and semantic type labels. Finally, two types of topology instances are generated: a strict topology containing only physically feasible links, and a hybrid topology containing both physically feasible links and logical links, thereby supporting different application requirements.

4.2 Orbital plane identification mechanism

4.2.1 Regular RAAN lattice assignment

In existing research, orbital planes are typically partitioned by the RAAN. But in practice, due to factors like orbital perturbations, the RAAN values of satellites within the same orbital plane typically exhibit perturbations, making methods based on simple thresholds or unconstrained clustering prone to misclassification in boundary regions.

To address this issue, this paper proposes a regular RAAN lattice assignment method. Leveraging the prior knowledge that orbital planes in a Walker constellation are approximately equally spaced [19], the orbital plane identification problem is transformed from an unconstrained clustering problem into a one-dimensional alignment problem by searching for a global offset.

Let the number of orbital planes in the constellation be N_p , and the ideal spacing between adjacent orbital planes be $\Delta\Omega = \frac{360^\circ}{N_p}$. Given a global offset $\theta_0 \in [0, \Delta\Omega)$, the RAAN lattice centre of the k -th orbital plane is:

$$\Omega_k = (\theta_0 + k\Delta\Omega) \bmod 360^\circ, k = 0, 1, \dots, N_p - 1 \quad (12)$$

Each satellite is assigned to the nearest lattice centre, i.e., the orbital plane with minimum circular RAAN residual:

$$pid = \arg \min_k d_{\text{circ}}(\Omega_s, \Omega_k(\theta_0)) \quad (13)$$

Since the RAAN values are distributed within the range $[0^\circ, 360^\circ)$ and exhibit periodicity, the conventional absolute difference cannot characterize circular angular adjacency accurately. Therefore, to measure the difference between two RAAN angles, a circular distance d_{circ} is defined as:

$$d_{\text{circ}}(a, b) = \min(|a - b| \bmod 360^\circ, 360^\circ - |a - b| \bmod 360^\circ) \quad (14)$$

By performing a discrete search of the offset within the range $[0, \Delta\Omega)$ the offset θ_0^* that minimizes the cost function is selected as the approximate optimal solution:

$$\theta_0^* = \arg \min_{\theta_0 \in [0^\circ, \Delta\Omega)} \left[\frac{1}{N} \sum_{s=1}^N d_{\text{circ}}^2(\Omega_s, \Omega_{pid(s, \theta_0)}(\theta_0)) + \lambda \sigma(\mathbf{c}(\theta_0)) \right] \quad (15)$$

where $\mathbf{C}$ is the vector of satellite counts per orbital plane, $\sigma(\cdot)$ is the standard deviation and $\lambda = 0.02$ is a balance coefficient. The offset search step size is 0.05° , with dense scanning over the range $[0^\circ, 5^\circ)$. When there is a significant imbalance in lattice distribution results, a circular 1D K-means refinement procedure is applied to account for the periodic characteristics of RAAN angles. Using the lattice assignment results as initial cluster centres, the orbital plane boundaries are further refined and optimized.

The implementation procedure of the regular RAAN lattice assignment method is presented in Algorithm 1.

Algorithm 1: Regular RAAN Lattice Assignment

Input: satellites RAAN set $\{\Omega_s\} (s = 1, \dots, N)$; number of orbital planes N_p ; search step size $\Delta\theta = 0.05^\circ$

Output: orbital plane labels $\{pid(s)\}$; optional offset θ_0^* ; lattice centres $\Omega_k(\theta_0^*)$

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1:  $\Delta\Omega \leftarrow \frac{360^\circ}{N_p}$ 
2: score*  $\leftarrow +\infty$ 
3: for  $\theta_0 = 0, \Delta\theta, 2 \times \Delta\theta, \dots, \Delta\Omega - \Delta\theta$  do
4:   for  $k = 0, \dots, N_p - 1$ :  $\Omega_k(\theta_0) \leftarrow (\theta_0 + k\Delta\Omega) \bmod 360^\circ$ 
5:   for  $s = 1, \dots, N$ :  $pid(s) \leftarrow \arg \min_k d_{\text{circ}}(\Omega_s, \Omega_k(\theta_0))$ 
6:    $c(\theta_0) \leftarrow$  satellite count vector of each orbital plane;  $\sigma \leftarrow \text{std}(c(\theta_0))$ 
7:   score  $\leftarrow \frac{1}{N} \sum_{s=1}^N d_{\text{circ}}^2(\Omega_s, \Omega_{pid(s)}(\theta_0)) + \lambda \sigma(c(\theta_0))$ 
8:   if score < score*: score*  $\leftarrow$  score;  $\theta_0^* \leftarrow \theta_0$ ; pid*  $\leftarrow$  pid
9: end for
10: counts  $\leftarrow c(\theta_0^*)$ ; expected  $\leftarrow \frac{N}{N_p}$ 
11: if max(counts) > 1.6 · expected or min(counts) < 0.4 · expected:
12:   pid*  $\leftarrow$  CircularKMeans1D( $\{\Omega_s\}$ ,  $N_p$ , init= $\{\Omega_k(\theta_0^*)\}$ )
13: if imbalance still exists then:
14:   pid*  $\leftarrow$  ContiguousRAANPartition( $\{\Omega_s\}$ ,  $N_p$ )
15: return pid*,  $\theta_0^*$ ,  $\{\Omega_k(\theta_0^*)\}$ 

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4.2.2 Intra-plane slot mapping

After orbital plane assignment, satellites within each plane are further mapped onto 22 ordered logical slots to characterize their relative positions along the orbital ring structure. This mapping establishes a consistent correspondence between each satellite and its structural position within the intra-plane topology.

For orbital plane p , the phase centres of the 22 logical slots are defined as:

$$\psi_s^{(p)} = \left(\theta_p + s \times \frac{360^\circ}{22} \right) \bmod 360^\circ, \quad s = 0, 1, \dots, 21 \quad (16)$$

where θ_p is the optimal phase offset of orbital plane. Each satellite is assigned to the slot that minimizes its mean anomaly residual; in case of conflicts, assignment is prioritized in ascending order of residual, ensuring that each slot is occupied by at most one satellite.

After slot mapping, each satellite holds a unique tuple $(pid, seat_idx)$, which plays a key role in the phase matching for inter-plane link assignment and the cost computation in Phase 2 link repair.

4.2.3 Seam plane detection

In a Walker Delta constellation, among N_p prograde orbital planes, there exists one pair of adjacent orbital planes in a counter-rotating state [20], with a relative velocity approximately twice that between co-rotating planes. This special orbital plane pair is referred to as the seam plane.

Seam-plane pairs are identified based on the RAAN difference between adjacent orbital planes:

$$\text{IsSeam}(p_a, p_b) = \begin{cases} \text{True} & \text{if } \text{IsAdjacent}(p_a, p_b), d_{\text{circ}}(\Omega_{p_a}, \Omega_{p_b}) > \theta_{\text{seam}} \\ \text{False} & \text{otherwise} \end{cases} \quad (17)$$

In this paper, the seam plane RAAN threshold is set to $\theta_{\text{seam}} = 170^\circ$, while adjacent orbital planes $\text{IsAdjacent}(p_a, p_b)$ are restricted to neighbouring plane pairs with cyclic index differences no greater than one. For orbital plane pairs identified as seam planes, inter-plane links are prohibited to avoid the adverse impact of high relative motion links on structural stability.

4.3 Two-phase topology generation strategy

To jointly preserve structural regularity and physical feasibility, a two-phase topology generation strategy is adopted to construct regular mesh-like topology. In Phase 1, structured topology construction is performed based on orbital plane geometric relationships to establish the network skeleton. In Phase 2, link supplementation is performed on under-connected nodes to repair local structural defects.

4.3.1 Phase 1: Structured topology construction

The objective of Phase 1 is to establish the structured network backbone by recovering the characteristic intra-plane ring and inter-plane grid connectivity of Walker Delta constellations under physical constraints. More specifically, each satellite maintains two intra-plane connections with neighbouring satellites along the same orbital track and two inter-plane connections with phase-aligned satellites in adjacent orbital planes.

For intra-plane link construction, active satellites within the same orbital plane are sorted in ascending order according to their real-time phase angles to form a compressed ring structure. When vacant positions exist, the remaining

satellites are reorganized into a continuous ring to prevent intra-plane link disconnections caused by slot vacancies. Each satellite s_i in the compressed ring attempts to establish forward and backward intra-plane connections. The generated intra-plane links are then processed according to the two output modes defined in Section 3.3.2. If a link satisfies physical constraints, it is labelled as a physical link; if a link maintains structural continuity but temporarily exceeds the physical distance threshold due to instantaneous geometric variations without Earth blockage, it is labeled as a logical link. Under the hybrid mode, both physical links and logical links are retained, where logical links are used to preserve topology structural continuity and semantic representation without participating in actual data transmission or link scheduling. Under the strict mode, only physically feasible links satisfying all physical constraints are retained, while other links are discarded.

For inter-plane link construction, satellites with at least one intra-plane link search for phase-aligned neighbouring satellites in the right and left adjacent orbital planes. The neighbour search adopts a dual-stage filtering strategy of "slot-priority with distance assistance". First, candidate satellites whose slot index offsets do not exceed two are selected within the target orbital plane. The candidates are then sorted in ascending order according to geometric distance, and the first candidate satisfying all constraints is selected to establish an inter-plane link.

For seam orbital plane pairs with significant relative motion, inter-plane links are explicitly prohibited to avoid structural instability caused by highly dynamic connections.

4.3.2 Phase 2: Hierarchical link supplementation

Phase 2 performs local structural repair on the topology generated in Phase 1 under the dual-semantic topology framework. Due to factors such as instantaneous geometric perturbations, seam-plane restrictions and uneven local satellite distributions, some satellites may still suffer from insufficient degrees after Phase 1. To address this issue, a hierarchical link supplementation mechanism is adopted under the dual-semantic framework. The link supplementation process is strictly constrained within existing link categories and does not introduce additional link types. The supplementation priorities are defined as follows:

Intra-plane link supply: Search for unconnected physically feasible satellites within the same orbital plane.

Adjacent-plane link supply: Perform global matching link supplementation for under-connected satellites between adjacent orbital planes.

For supplementation between adjacent orbital planes, a hierarchical strategy is applied. First, a local greedy strategy is used to generate candidate connections. When competitive conflicts arise among candidate satellites, the Hungarian algorithm is introduced to perform globally optimal matching, thus avoiding link assignment conflicts and structural irregularities caused by local competition. For an orbital plane pair (p_a, p_b) , let the sets of under-connected

satellites on both sides be U_p and $U_{p'}$. The cost matrix C is constructed with elements defined as:

$$C_{ij} = \begin{cases} (\Delta s_{ij}, \Delta \psi_{ij}, d_{ij}) & \text{if } \Delta s_{ij} \leq \delta_{\text{inter}} \\ +\infty & \text{otherwise} \end{cases} \quad (18)$$

where $\Delta s_{ij} = |\text{seat}(u_i) - \text{seat}(v_j)|_{\text{ring}}$ is the slot index difference, $\Delta \psi_{ij} = d_{\text{circ}}(M_{u_i}, M_{v_j})$ is the mean anomaly difference, and $d_{ij} = \|\mathbf{r}_{u_i} - \mathbf{r}_{v_j}\|_2$ is the ECEF distance.

The cost matrix design follows the principle of "slot alignment first, phase matching second, and distance minimization as fallback". Concretely, slot index difference directly reflects the relative positions of satellites within the orbital ring structure and therefore receives the highest weight. Mean anomaly difference is used to characterize the consistency of orbital motion states and serves as a physical-level supplement to slot alignment, thus receiving a moderate weight. Distance is assigned the lowest weight because, once the first two conditions are satisfied, distance differences are typically small and have limited impact on link quality.

After applying the Hungarian algorithm to the cost matrix, a candidate link is added to the topology only if the resulting matching satisfies both physical feasibility constraints and semantic consistency conditions.

5. EXPERIMENTAL RESULTS AND ANALYSIS

5.1 Experimental setup

This paper uses the Starlink 550 km / 53° constellation shell as the experimental subject, with TLE data publicly released by CelesTrak on 2 April 2026 as the data source. After filtering by inclination ($53.0^\circ \pm 0.3^\circ$) and orbital altitude (550 ± 30 km), the number of effective satellites participating in graph construction at each time step is stable at 1421.

The simulation spans 300 consecutive time frames with a sampling interval of 180 s, resulting in a total duration of 54 000 s (approximately 15 hours), covering about 9.4 complete orbital periods.

Table 5-1 – Core parameter settings

Parameter	Symbol	Value
Maximum ISL distance threshold	d_{max}	2175 km ($1.10 \times$ nominal intra-plane spacing)
Maximum antenna slots	k	4
Number of orbital planes	N_p	72
Number of intra-plane slots	s	22
Lattice offset search step size	–	0.05°
Time step	Δ_t	180 s
Number of simulation frames	N_{frame}	300

Table 5-1 summarizes the key parameters involved in topology generation. Among them, the distance threshold and time step directly determine the physical topology constraints and temporal discretization granularity, respectively. Their sensitivity is further analysed in Section 5.5, while the remaining structural parameters are directly determined by the publicly available Starlink constellation configuration.

5.1.1 Evaluation metrics

To quantitatively evaluate the generated dynamic topologies, several metrics are adopted from graph analysis and temporal network evaluation, including link similarity, connectivity, topology stability and prediction consistency.

Jaccard similarity: The Jaccard similarity coefficient is used to measure the similarity of link sets between two consecutive topology snapshots. Given two adjacent topology snapshots $G_t = (V, E_t)$ and $G_{t+1} = (V, E_{t+1})$, it is defined as:

$$J(E_t, E_{t+1}) = \frac{|E_t \cap E_{t+1}|}{|E_t \cup E_{t+1}|} \quad (19)$$

A higher Jaccard value indicates fewer link changes between consecutive snapshots and therefore better temporal stability.

Largest Connected Component ratio (LCC ratio): LCC ratio is adopted to evaluate global network connectivity. It is defined as:

$$LCC = \frac{|V_{\max}|}{|V|} \quad (20)$$

where $V_{\max}$ denotes the set of nodes contained in the largest connected component, and V represents the set of all satellite nodes in the network. A value close to 1 indicates that most satellites belong to a single connected network.

5.2 Validation of constellation topology generation

Before analysing the generated topologies, the geometric characteristics of the filtered constellation samples are first validated to ensure the quality of the dataset and the rationality of the orbital distribution. Fig. 5-1 presents multidimensional diagnostic results of the constellation structure from several aspects, including orbital altitude distribution, latitude coverage, longitudinal stripe patterns, longitude–latitude spatial distribution, orbital plane occupancy and orbital plane size distribution.

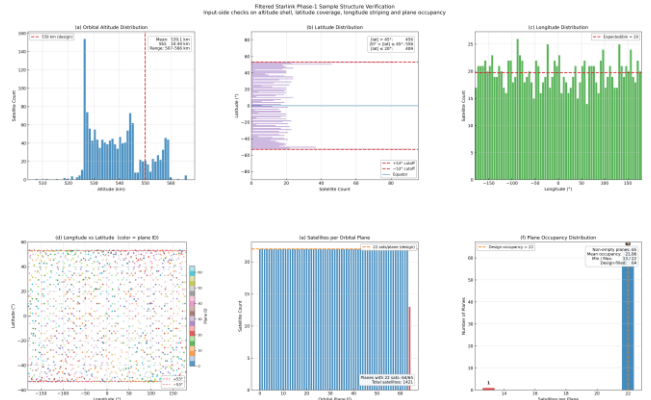


Figure 5-1 – Starlink constellation (550 km, 53° inclination) structure validation

As shown in Fig. 5-1(a), the mean orbital altitude of the 1421 effective satellites is 539.1 km with a standard deviation of 10.44 km, concentrated near the 550 km design altitude. Fig. 5-1(b) shows that the subsatellite-point latitudes are strictly bounded within $\pm 53^\circ$, consistent with the target orbital inclination. Figures 5-1(c) and 5-1(d) further reveal clear longitudinal stripe patterns, reflecting the characteristic multi-plane organization of the constellation.

Figures 5-1(e) and 5-1(f) show that among the 65 effective orbital planes, 64 each contain 22 satellites. These verification results demonstrate that the filtered constellation data is in strong agreement with Starlink 550 km, 53° orbital shell configuration across four dimensions, orbital altitude, latitude coverage, longitude uniformity and orbital plane integrity, and can be used as a reliable input for subsequent topology generation experiments.

Figures 5-2 and 5-3 present the hybrid mode topological structure at time $t = t_0$ from two-dimensional (2D) map projection and three-dimensional (3D) spherical perspectives. Since the hybrid mode simultaneously preserves physically feasible links and logical links, it is first analysed through visualization. The strict mode is subsequently used as a baseline for evaluating physical feasibility in the following sections

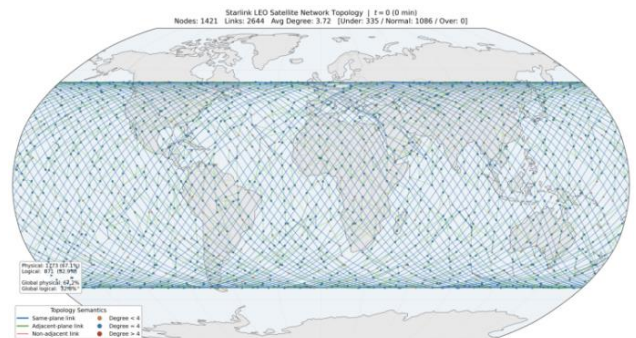


Figure 5-2 – 2D map projection of LEO satellite network topology ($t = t_0$, hybrid mode)

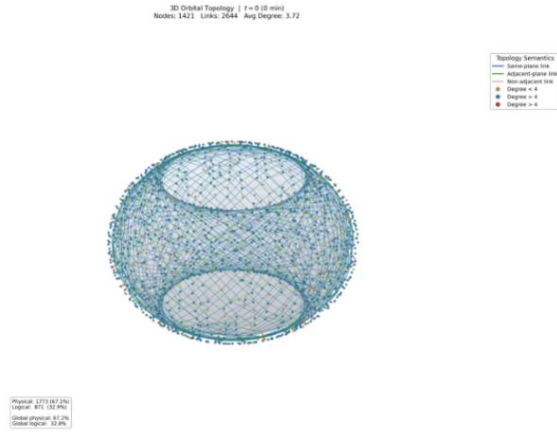


Figure 5-3 – 3D spherical view of LEO satellite network topology ($t = t_0$, hybrid mode)

In the 2D projection of Fig. 5-2, intra-plane links (cyan) form continuous ring chains along the orbital direction, while inter-plane links (blue) form a regular cross-plane mesh. Together, they constitute a globally distributed grid-like topology. In the 3D spherical view of Fig. 5-3, the topology presents a regular spherical grid structure, where intra-plane ring links and inter-plane grid links are clearly distinguishable. This verifies the effectiveness of the proposed structured topology construction and hierarchical link supplementation mechanisms in reconstructing the regular topology of Walker constellations in 3D space.

5.3 Analysis of topology generation results

5.3.1 Different topology generation methods

To evaluate the performance of the proposed method, two topology generation approaches, namely KNN and grid, are selected as comparison baselines. Meanwhile, the strict mode topology generated by the proposed method is used as a reference under strict physical constraint conditions.

KNN: For each satellite, the four nearest satellites are selected from feasible neighbours satisfying distance and Earth blockage constraints to establish links. This method represents real-time geometry-based nearest-neighbour topology construction approaches.

Grid: According to the Walker constellation structure, each satellite establishes links with the two forward and two backward satellites within the same orbital plane, as well as one satellite from each adjacent orbital plane. Neighbour selection is based only on the nearest geometric distance. This method represents fixed-rule-based real-time topology construction approaches.

5.3.2 Comparative results analysis

All four methods use the same 300-frame satellite state sequences driven by real TLE data as inputs. The maximum node degree is uniformly set to 4 to ensure a fair comparison. Table 5-2 presents the statistical results of the four methods over the 300-frame simulation window from four perspectives: structural scale, connectivity, temporal stability, and physical characteristics.

Table 5-2 – Comparison of four topology generation methods (Average over 300 frames)

Metric	KNN	Grid	Strict	Hybrid
Average number of edges	2587.82	2505.14	1845.11	2646.16
Average node degree	3.642	3.526	2.597	3.724
Isolated node ratio	0.211%	0.000%	0.385%	0.000%
Largest connected component ratio	97.46%	100%	98.93%	100%
Number of connected components	7.85	1.00	10.50	1.00
Adjacent-frame edge Jaccard similarity	0.239	0.979	0.922	0.951
Average link distance (km)	473.3	1998.8	1100.8	1614.8
Maximum link distance (km)	1726.9	252 167.5	2175.0	5436.7
Graph density	0.00256	0.00248	0.00183	0.00262
Average clustering coefficient	0.426	0.180	0.080	0.052

The comparison results show that the KNN method achieves an average node degree (3.642) close to the target value, and all generated links satisfy physical feasibility constraints. However, its adjacent-frame edge Jaccard similarity is only 0.239, indicating that approximately 76% of links are replaced in the next frame. This demonstrates that the frame-by-frame independent nearest-neighbour selection strategy is highly sensitive to instantaneous orbital geometry variations and lacks structural continuity.

The grid method achieves high temporal stability (Jaccard similarity = 0.979) and complete connectivity (LCC = 100%) through fixed structural rules. However, since neighbour selection does not incorporate physical feedback constraints, cross-plane neighbours may select candidates far beyond engineering feasibility in sparse orbital plane regions. The maximum link distance reaches 252 167.5 km, indicating the risk of generating physically infeasible links. Moreover, its average clustering coefficient (0.180) is lower than that of KNN, indicating insufficient local structural regularity.

The strict mode improves temporal stability from 0.239 of KNN to 0.922 while maintaining physical feasibility through structured link construction, validating the contribution of the structured topology construction mechanism in Section 4.3 to temporal stability. However, due to strict distance constraints, the average node degree is only 2.597. An average of 10.50 connected components appears within the 300-frame simulation window, with the largest connected component ratio reaching 98.93%. This indicates that approximately 1% of nodes are disconnected from the main network and form isolated clusters in each frame, requiring additional upper-layer mechanisms for network access management.

The hybrid mode achieves comparable temporal stability to the grid method (0.951) and complete connectivity (LCC = 100%, the number of connected components remains constantly 1, with no isolated clusters). Meanwhile, it achieves the highest average node degree (3.724) and graph density (0.00262) among the four methods. Furthermore, all inter-plane links remain 100% physically feasible.

These results demonstrate that the proposed two-stage topology generation strategy successfully decouples the continuous geometric evolution of satellite motion from topology-level structural characteristics. The dual-semantic topology representation preserves realistic orbital dynamics while maintaining stable long-term structural adjacency relationships of Walker constellations, achieving the design objective of "dynamic geometry with structural continuity".

5.3.3 Analysis of topology stability and dynamic characteristics

To evaluate the stability of topology sequences during continuous orbital evolution, this paper analyses the adjacent-frame variations of the hybrid mode topology over the 300-frame simulation window.

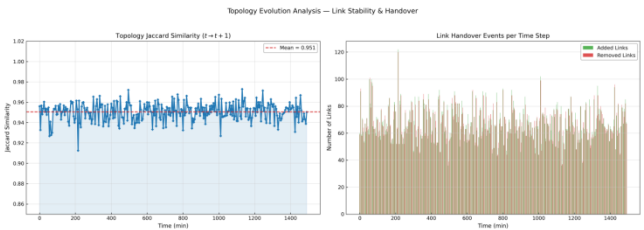


Figure 5-4 – Topology temporal stability analysis (hybrid mode, 300 frames)

Fig. 5-4 further validates this property from the perspective of inter-frame topology variation. As shown in the left panel of Fig. 5-6, the average Jaccard similarity between adjacent topology snapshots reaches 0.951 and remains highly stable throughout the entire simulation window, with no noticeable long-term drift trend. Under the 180 s sampling interval, this corresponds to an average link-switching ratio of approximately 4.9% per frame, meaning that roughly 130 links are added or removed among approximately 2646 links between consecutive snapshots. The right panel of Fig. 5-4 shows that the numbers of link additions (green) and removals (red) fluctuate symmetrically within the range of 20–120 events per frame, indicating that the overall topology scale remains stable during temporal evolution.

5.4 Analysis of dual-semantic output modes

To further analyse the impact of the dual-semantic topology output mechanism on topology structure and network performance, this paper compares the strict and hybrid modes from two perspectives: the link construction process and performance characteristics.

5.4.1 Analysis of link construction process in strict and hybrid modes

To investigate the differences between the two topology output modes during topology generation, the cumulative number of links generated at each construction stage of the hybrid and strict modes over the 300-frame simulation window is statistically analysed. The results are presented in Table 5-3.

Table 5-3 – Analysis of link construction results under two modes (global cumulative results over 300 frames)

Construction Phase	Hybrid Link Count	Hybrid Proportion	Strict Link Count	Strict Proportion
Phase 1 Intra-Plane Link Construction	419 405	52.8%	159 097	28.7%
Phase 1 Inter-Plane Link Construction	339 926	42.8%	339 926	61.4%
Phase 2 Link Supplementation	34 517	4.3%	54 509	9.8%
Total	793 848	100%	553 532	100%

As shown in Table 5-3, the two modes generate exactly the same number of links during Phase 1 inter-plane link construction, with both producing 339 926 links. The primary difference between the two modes occurs in the Phase 1 intra-plane link construction stage. The hybrid mode generates 260 308 more links than the strict mode, and this difference exactly corresponds to the total number of logical links introduced in the hybrid mode. This indicates that inter-plane link generation is mainly governed by physical constraints, while the logical link generation mechanism does not affect inter-plane slot assignment.

In contrast, the strict mode generates 54509 supplementary links during Phase 2, which is significantly higher than the 34 517 links generated in the hybrid mode. This demonstrates that without logical link support, the strict mode requires more subsequent repairs to compensate for low-degree nodes and local structural gaps.

The above results indicate that the strict mode emphasizes instantaneous physical validity, whereas the hybrid mode further preserves structural continuity by introducing logical semantics. Therefore, the two modes satisfy different topology representation requirements: the description of physical communication states and the representation of structurally stable topologies.

5.4.2 Performance analysis of dual-semantic modes

To further analyse the impact of the dual-semantic output mechanism on topology structural integrity and connectivity, this paper compares the strict and hybrid modes in terms of link scale, node connectivity, and network completeness. The results are presented in Table 5-4.

Table 5-4 – Core metric comparison of hybrid mode vs. strict mode (global cumulative results over 300 frames)

Metric	Hybrid	Strict
Average Edge Count	2646.16	1845.11
Average Node Degree	3.724	2.597
Physically Feasible Link Ratio	67.2%	100%
Logical Link Ratio	32.8%	0%
Final Frame Degree = 4 Node Count	1079	350
Final Frame Degree = 1 Node Count	1	96
Final Frame Degree = 0 Node Count	0	6

Table 5-4 compares the core performance metrics of the hybrid and strict modes. Under the strict mode, the average node degree is only 2.597. In the final frame, 6 satellites become completely isolated, while 96 satellites have only one connection, indicating that the network becomes fragmented into multiple disconnected subgraphs. In contrast, by introducing 32.8% logical links, the hybrid mode increases the average node degree to 3.724. The number of nodes with degree four in the final frame increases from 350 to 1079, achieving improvements in both global connectivity and node connection balance.

5.5 Ablation study

5.5.1 Experimental design

To validate the effectiveness of different components in the proposed method, ablation studies are conducted on two key modules: the orbital plane identification strategy and the hierarchical link supplementation mechanism.

Table 5-5 – Ablation experiment settings

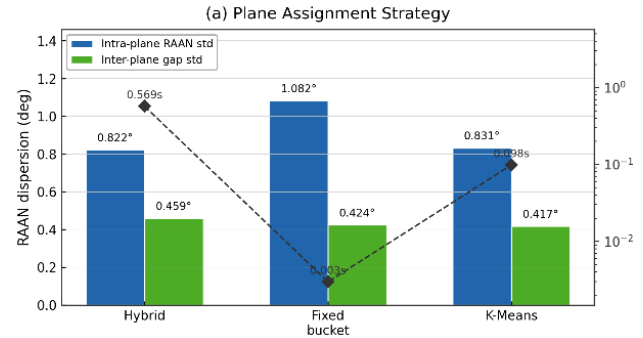
Ablation Group	Comparison Variables
A: Orbital Plane Identification Strategy	Regular RAAN lattice / Fixed binning / Adaptive K-Means
B: Hierarchical Link Supplementation Mechanism	Phase 2 enabled / Disabled

All ablation experiments are conducted based on the same 300-frame real TLE-driven orbital dataset described in Section 5.1, with a sampling interval of 180 s and a fixed random seed (seed = 42). This ensures that all experimental groups are evaluated under identical conditions and can be directly compared quantitatively.

5.5.2 Analysis of orbital plane identification strategies

To investigate the impact of orbital plane identification strategies on topology generation performance, three approaches, namely regular RAAN lattice assignment, fixed binning and adaptive K-means, are adopted for orbital plane partitioning. The subsequent seat mapping, Phase 1 link construction and Phase 2 link supplementation processes are kept identical for all approaches.

Unlike the independent baseline comparison of KNN and grid methods in Section 5.3, the ablation group A aims to isolate the impact of the orbital plane identification strategy as a single variable, rather than evaluating it as an independent topology generation method.

**Figure 5-5** – Ablation results of orbital plane identification strategies

As shown in Fig. 5-5, the regular RAAN lattice method achieves a more balanced orbital plane partition. Specifically, the standard deviation of orbital plane RAAN values is 0.822°, which is lower than 1.082° obtained by the fixed binning method. Meanwhile, the range of orbital plane occupancy is only 14, compared with 26 for the fixed binning method.

These results indicate that the lattice-based partitioning method, which exploits the continuous variation characteristics of RAAN values, can more accurately represent the orbital structure of Walker constellations and provide more stable and balanced inputs for subsequent structured slot mapping.

On the other hand, the differences in topology sequence variation rates among the three methods are relatively small (0.0492-0.0517), indicating that the orbital plane identification strategy mainly affects the balance of topology structure partitioning, while temporal stability is primarily determined by the subsequent structured link construction mechanism.

5.5.3 Analysis of hierarchical link supplementation mechanism

To validate the effectiveness of the Phase 2 hierarchical link supplementation mechanism, this section disables the supplementation stage and compares the results with the complete proposed method.

Table 5-6 – Ablation results of the hierarchical link supplementation mechanism

Metric	Phase 2 Enabled	Phase 2 Disabled
Average Node Degree	3.7244	3.5624
Degree Standard Deviation	0.5238	0.6252
Variation Rate	0.0495	0.0486

As shown in Table 5-6, enabling Phase 2 increases the average node degree from 3.5624 to 3.7244 and reduces the degree standard deviation from 0.6252 to 0.5238. This demonstrates that the supplementation mechanism effectively improves the node connectivity distribution and enhances structural balance of the network.

Meanwhile, the variation rates under the two settings remain almost unchanged, with values of 0.0495 and 0.0486, respectively. This indicates that the supplementation process mainly performs local structural repair and does not compromise the temporal stability of the existing topology.

Furthermore, during the supplementation stage, the Hungarian algorithm is adopted for node matching between adjacent orbital planes to avoid matching conflicts caused by local greedy strategies. Tests on the complete 300-frame dataset demonstrate that this matching process satisfies the requirements of offline topology generation.

Overall, the above results demonstrate that the orbital plane identification strategy provides a stable spatial partition foundation for structured topology construction, while the hierarchical link supplementation mechanism further improves local connectivity balance. Together, these two components enhance the quality of dynamic satellite network topology generation.

5.6 Parameter sensitivity analysis

5.6.1 Distance threshold

To validate the rationality of the distance threshold selection, the maximum ISL distance threshold described in Section 3.2 is configured with different engineering margins based on the nominal intra-plane spacing. Specifically, four margin settings, namely 5%, 10%, 15% and 20%, are adopted to regenerate the 300-frame hybrid and strict topology sequences. The results are presented in Table 5-7.

Table 5-7 – Sensitivity analysis of distance threshold

Engineering Margin	Maximum Distance Threshold (km)	Hybrid Average Edge Count	Hybrid Adjacent-frame Jaccard	Strict Average Edge Count	Strict Adjacent-frame Jaccard
5%	2075.5	2644.91	0.9512	1838.51	0.9219
10% (Default)	2174.3	2646.15	0.9506	1845.07	0.9217
15%	2273.1	2647.03	0.9502	1851.09	0.9211
20%	2372.0	2657.19	0.9485	1869.25	0.9158

The results demonstrate that the hybrid mode exhibits strong robustness to distance threshold selection. Within the range of 5%-15%, both the average edge count and adjacent-frame Jaccard similarity remain nearly unchanged, with edge count variation below 0.1% and Jaccard variation below 0.001. Only when the threshold margin is increased to 20% does the Jaccard similarity slightly decrease, while the increase in edge count becomes more significant (an increase of 11 links, compared with approximately 1 link increase between the previous two intervals).

This phenomenon indicates that the temporal stability of the hybrid mode mainly originates from the structured link construction mechanism and logical semantic representation, rather than relying on precise tuning of the distance threshold. Even with certain engineering deviations in threshold selection, the dual-semantic topology can still maintain stable outputs.

In contrast, the average edge count of the strict mode increases monotonically with the distance threshold, while its Jaccard similarity decreases as the threshold becomes larger. This indicates that without logical semantic support, the structural characteristics of the strict mode are more sensitive to the distance threshold. A larger threshold introduces more physical links located near the feasibility boundary, and some of these boundary links inherently exhibit higher frame-to-frame switching probability, thereby reducing overall temporal stability.

Overall, the default 10% engineering margin is located in the central region of the optimal performance interval of the hybrid mode, providing a robust parameter selection.

5.6.2 Time step

With the total simulation duration fixed at 54000 s, topology sequences are regenerated using six different time steps: 60 s, 120 s, 180 s, 240 s, 300 s, and 360 s, corresponding to 900, 450, 300, 225, 180, and 150 frames, respectively. The results are presented in Table 5-8.

Table 5-8 – Sensitivity analysis of time step

Time Step (s)	Number of Frames	Hybrid Average Edge Count	Hybrid Adjacent-frame Jaccard	Strict Average Edge Count	Strict Adjacent-frame Jaccard
60	900	2646.22	0.9719	1845.15	0.9522
120	450	2646.23	0.9570	1845.13	0.9288
180 (Default)	300	2646.16	0.9505	1845.11	0.9217
240	225	2646.20	0.9530	1845.03	0.9313
300	180	2646.37	0.9435	1845.13	0.9157
360	150	2646.13	0.9318	1845.13	0.8956

The results show that the average edge counts of both modes remain almost unchanged under all six time-step settings, with variations below 0.02%. This indicates that topology scale is mainly determined by orbital geometry and constellation structure, rather than the temporal discretization granularity.

The adjacent-frame Jaccard similarity generally decreases as the time step increases. Specifically, the hybrid mode decreases from 0.9719 at 60 s to 0.9318 at 360 s, while the strict mode decreases from 0.9522 to 0.8956. This trend is consistent with the physical intuition that a larger time step results in larger orbital phase differences between adjacent frames and therefore a higher probability of link switching.

It should be noted that this trend is not strictly monotonic. For example, the Jaccard similarity at 240 s is slightly higher than that at 120 s. This local fluctuation is caused by differences in phase alignment between the sampling interval

and the orbital period (approximately 5730 s), which represents normal geometric sampling variation and does not affect the overall trend.

Across all six time-step settings, the Jaccard similarity of the hybrid mode is consistently higher than that of the strict mode under the same time granularity, with differences ranging from 0.019 to 0.036. This demonstrates that the stability improvement introduced by the dual-semantic mechanism remains consistent under different temporal resolutions rather than being an incidental result under the default 180 s sampling interval, further supporting the general applicability of the proposed method.

5.7 Applicability analysis of topology for space computing tasks

This section further analyses the applicability of the generated topology sequences for typical downstream tasks in space computing networks, including dynamic graph learning and topology prediction, distributed task scheduling, and federated learning.

5.7.1 Applicability for dynamic graph learning and topology prediction

In dynamic graph learning and topology prediction tasks, a widely adopted baseline strategy is the persistence baseline, which directly uses the topology at the previous time step as the prediction result for the next time step. The prediction consistency of this baseline directly reflects the suitability of the input topology sequence for temporal modelling tasks: smoother structural evolution leads to higher prediction consistency and reduces the effective structural noise that learning models need to capture.

In this paper, the persistence baseline is evaluated on the 300-frame real topology sequences generated by the hybrid and strict modes. Here, the F1-score is used to measure the consistency between the predicted topology and the actual topology, where a higher value indicates fewer link variations between consecutive topology snapshots. The results are shown in Table 5-9.

Table 5-9 – Adjacent-frame link persistence prediction

Topology Type	F1
Hybrid (All links, including logical links)	0.9746
Strict (Physical links)	0.9592
Hybrid (Only physically feasible links extracted)	0.9623

The results show that the complete hybrid topology sequence achieves an F1 score of 0.9746 under this baseline task, which is significantly higher than the 0.9592 achieved by the strict mode. This indicates that when the hybrid topology sequence is directly used as the input topology sequence for dynamic graph learning models, it introduces fewer cross-frame label transitions, thereby reducing adjacency relationship drift and label noise.

More importantly, even when only the physically feasible links in the hybrid topology are retained (i.e., removing

logical links to obtain a subnetwork semantically comparable with the strict mode), the persistence F1 score remains 0.9623, which is still higher than that of the strict mode (0.9592). This result indicates that the contribution of the hybrid mode to temporal stability is not solely attributed to the explicitly preserved logical links. Instead, it also improves the temporal consistency of the physically executable network itself by reducing the frequency of Phase 2 link supplementation (Table 5-3, where the Phase 2 supplementation ratio of hybrid is 4.3%, lower than 9.8% of strict).

This provides additional quantitative evidence for the relationship between the hierarchical link supplementation mechanism described in Section 4.3.2 and temporal stability.

5.7.2 Connectivity analysis for distributed task scheduling and federated learning

Distributed on-orbit task scheduling and federated learning aggregation both rely on network-wide or large-scale subnetwork connectivity to ensure the reachability of task migration paths or gradient aggregation paths.

In this paper, the communication graph composed of physically feasible links is analysed. The number of connected components and the Largest Connected Component ratio (LCC ratio) are calculated over the 300-frame simulation window.

For the strict mode, the average number of connected components is 10.50, indicating that approximately 10 isolated subnetworks exist in each frame on average. These disconnected subnetworks cannot participate in global task coordination directly and require additional upper-layer scheduling mechanisms to handle isolated node access.

In contrast, the hybrid mode maintains an LCC ratio of 100% throughout all 300 frames, with no isolated subgraphs requiring special processing.

Regarding routing cost, this paper further considers the largest connected component formed by physically feasible links and calculates the average shortest-path hop count. The hybrid and strict modes achieve 28.34 hops and 27.57 hops, respectively, with standard deviations below 0.3 hops for both modes. The difference between the two modes is less than 3%, indicating that the hybrid mode eliminates connectivity fragmentation and reduces task scheduling complexity without introducing significant additional hop costs for task migration or gradient aggregation.

Overall, the results in this section demonstrate that the hybrid topology sequence, while maintaining consistency with real physical constraints, simultaneously provides lower downstream task label noise and more complete global connectivity. Therefore, it offers a more suitable underlying topology representation for space computing tasks such as dynamic graph learning, distributed task scheduling, and federated learning.

It should be noted that the persistence prediction and connectivity analysis adopted in this section are quantitative proxy metrics designed according to downstream task

characteristics, rather than end-to-end training experiments conducted on actual GNN models or federated learning systems. The latter requires more computational resources and engineering implementation efforts, and it is considered an important direction for future work.

6. CONCLUSION

This paper addresses the frequent topological variations and structural instability caused by high-speed orbital motion in LEO satellite networks and proposes a large-scale LEO satellite network topology generation method based on physical-logical semantic decoupling. By decoupling physical semantics and logical semantics in dynamic topologies, a dual-semantic topology representation framework is established, which simultaneously preserves realistic communication constraints and structural continuity. By integrating RAAN lattice-based orbital plane identification, structured topology construction, and hierarchical link supplementation mechanisms, the proposed method achieves dynamically stable topology generation for Walker constellations. Furthermore, two output modes, namely the strict mode and the hybrid mode, are provided, corresponding to physically executable real-time communication networks and space computing task topologies that preserve stable structural adjacency relationships, respectively.

Experimental results demonstrate that the proposed method can effectively reconstruct the regular structure of Walker constellations. Compared with the KNN and geometry-aware grid baseline methods, the proposed method significantly improves temporal topology stability and structural integrity while maintaining physical feasibility. Ablation experiments further validate the independent contributions of orbital plane identification, hierarchical link supplementation and the dual-semantic mechanism. The results indicate that the structured design is the primary contributor to temporal stability improvement, while the dual-semantic mechanism plays a critical role in connectivity recovery. Parameter sensitivity analysis and applicability evaluation for dynamic graph learning and distributed task scheduling further demonstrate that the generated hybrid topology maintains stable outputs under different engineering configurations and provides lower-noise and more completely connected topology inputs for downstream space computing tasks.

Future work will further investigate dynamic routing optimization, multi-satellite collaborative task scheduling, and topology prediction methods for space computing networks based on the proposed framework, promoting the evolution of LEO satellite networks toward intelligent space networks.

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