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A Review of Routing Technologies for Low Earth Orbit Satellite Networks: Dynamic Topology, Load Balancing, and QoS Assurance

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Abstract: Low Earth orbit (LEO) satellite networks feature periodic topology changes, frequent inter-satellite link handovers, uneven traffic, and constrained onboard resources, making efficient routing challenging. This paper systematically reviews LEO satellite routing technologies. First, routing is formulated as a time-varying graph optimization problem involving delay, bandwidth utilization, reliability, and control overhead. Existing schemes are then classified into topology-driven conventional routing and traffic-, load-, and QoS-aware adaptive routing, with their principles, advantages, limitations, and application scenarios comparatively analyzed. The results indicate that LEO routing is shifting from topology-based connectivity maintenance to service-oriented resource orchestration. Future architectures should combine orbit-based topology prediction and route precomputation with real-time state sensing and localized adjustment, thereby balancing scalability, route stability, resource utilization, and differentiated QoS assurance under dynamic traffic conditions.

Keywords: LEO satellite network; Dynamic topology; Routing algorithm; Load balancing; QoS routing.

1. Introduction

Low Earth orbit (LEO) satellite networks are becoming an essential component of space–air–ground integrated networks, providing wide-area broadband access, low-latency data delivery, and resilient connectivity for remote sensing, emergency communications, maritime and aeronautical services, and the Internet of Things [1]. Compared with geostationary satellite systems, LEO constellations substantially reduce propagation delay and path loss through lower orbital altitudes. Their large-scale deployment and dense inter-satellite connectivity also enable traffic to be forwarded through space-based multi-hop paths, reducing dependence on terrestrial gateways.

These advantages, however, introduce distinctive routing challenges. High-speed orbital motion continuously changes satellite visibility and periodically switches inter-satellite and satellite–ground links, yielding a time-varying topology with limited path lifetimes. Meanwhile, nonuniform user distribution and geographically correlated traffic can create persistent hotspots, particularly near gateway coverage areas and high-demand regions. Limited onboard processing capacity, buffer space, link bandwidth, and energy supply further constrain route computation and packet forwarding [2]. Consequently, shortest-path schemes based solely on hop count or propagation distance may direct excessive traffic toward a small set of links, resulting in buffer overflow, elevated queuing delay, packet loss, and premature route invalidation.

Routing in LEO satellite networks is therefore a multi-objective optimization problem over a predictable yet dynamically evolving graph. Besides reachability and propagation delay, route selection should jointly account for residual bandwidth, queue occupancy, link reliability, path lifetime, handover frequency, energy expenditure, and signaling overhead. These objectives are often conflicting: a minimum-delay path may have insufficient residual capacity, whereas a reliable or lightly loaded path may require additional hops. Moreover, frequent global state dissemination can improve decision accuracy but consumes scarce inter-satellite resources and may introduce stale information; aggressive route adaptation, in turn, risks route oscillation, packet reordering, and control-plane instability.

Existing studies address these issues through topology-driven routing, traffic- and load-aware path selection, multipath forwarding, congestion avoidance, and quality-of-service (QoS)-oriented resource allocation [10]. Nevertheless, differences in network assumptions, routing metrics, and evaluation scenarios make their performance boundaries difficult to compare systematically. Accordingly, this paper models LEO routing using a time-varying graph and identifies the principal link-cost components and performance objectives. It then classifies representative approaches according to the information used in routing decisions, examining their mechanisms, strengths, limitations, and applicable conditions. Finally, the paper discusses the transition from topology-oriented connectivity maintenance to service-oriented resource orchestration and argues that future architectures should combine orbital-predictive route precomputation with selective real-time state sensing and localized adaptation, thereby balancing scalability, stability, resource efficiency, and differentiated QoS assurance.

2. Satellite Network Architecture and Routing Problem Model

2.1. Satellite Network Architecture and Routing Characteristics

A typical LEO satellite communication system consists of a space segment, a ground segment, and user access networks. The space segment contains satellites distributed across multiple orbital planes. Each satellite communicates with neighboring satellites through inter-satellite links (ISLs), which may include intra-plane links between satellites in the same orbit and inter-plane links connecting adjacent orbital planes. The ground segment comprises gateways, network control centers, and terrestrial backbone facilities, whereas user terminals establish satellite–ground links (SGLs) to access the constellation. With onboard processing and packet-forwarding capabilities, traffic can be transmitted across several satellites and subsequently delivered through a suitable gateway, rather than being immediately relayed to the ground.

This architecture gives rise to several distinctive routing characteristics. First, orbital motion continuously changes satellite positions and link geometries. Some ISLs remain relatively stable, especially those between neighboring satellites in the same orbital plane, while others may be temporarily unavailable because of excessive distance, antenna-steering limitations, or rapidly varying relative motion. Satellite–ground associations are even more dynamic, as user terminals and gateways must switch their serving satellites periodically. Nevertheless, these topology changes are largely deterministic. Orbital ephemerides permit future connectivity to be predicted, enabling routing tables or candidate paths to be prepared before topology transitions occur [3].

Second, traffic conditions do not follow the same deterministic pattern. Demand varies across geographical regions and service periods, while gateway deployment may further concentrate flows in particular parts of the constellation. Consequently, certain ISLs can become congested even when the network remains physically connected. Third, routing is constrained by limited onboard processing capacity, buffer space, link bandwidth, and energy. A protocol requiring continuous global-state exchange may therefore generate disproportionate control overhead. Finally, different applications impose heterogeneous performance requirements. Routing must accommodate delay-sensitive, bandwidth-intensive, reliability-critical, and best-effort services without destabilizing the forwarding system. The fundamental challenge is thus to coordinate predictable topology evolution with uncertain traffic dynamics under constrained spaceborne resources.

2.2. Time-Varying Graph and Routing Optimization Model

The satellite network at time t can be represented as a time-varying directed graph [9]

$$G(t) = \big(V(t), E(t)\big),$$

where V(t) denotes the set of satellite nodes and, when necessary, accessible ground nodes, while E(t) contains all available ISLs and SGLs. For two nodes i and j, the binary connectivity variable $a_{ij}(t)$ is defined as

$$a_{ij}(t) = \begin{cases} 1, & (i,j) \in E(t), \\ 0, & otherwise. \end{cases}$$

A feasible route for flow f, denoted by $P_f(t)$, is an ordered sequence of links connecting its source s_f to destination d_f. Every link on this route must remain available during packet transmission; moreover, its assigned traffic should not exceed the effective capacity $C_{ij}(t)$. To capture both geometric and operational factors, the cost of link (i,j) may be expressed as

$$w_{ij}^{f}(t) = \alpha_f d_{ij}^{\text{prop}}(t) + \beta_f d_{ij}^{\text{queue}}(t) + \gamma_f \rho_{ij}(t) + \delta_f \ell_{ij}(t),$$

Where $d_{ij}^{prop}(t)$ and $d_{ij}^{queue}(t)$ represent propagation and queueing delays, respectively; $\rho_{ij}(t)$ denotes link utilization; and $l_{ij}(t)$ describes packet-loss risk or link unreliability. The coefficients α_f, β_f, γ_f, and δ_f reflect the QoS priorities of flow f. The corresponding routing problem can then be formulated as

$$\min_{\{P_f(t)\}} \sum_{f} \sum_{(i,j)\in P_f(t)} w_{ij}^{f}(t),$$

subject to path continuity, link-availability, capacity, and service-specific QoS constraints. For example, a delay-sensitive flow may require

$$\sum_{(i,j)\in P_f(t)} \left(d_{ij}^{\text{prop}}(t) + d_{ij}^{\text{queue}}(t)\right) \le D_f^{\max},$$

where D_f^{max} is its maximum acceptable end-to-end delay.

In practice, these objectives cannot always be optimized simultaneously. Shortest-path routing reduces propagation delay but may overload central links; aggressive load balancing alleviates congestion yet can increase hop count, control traffic, and packet reordering. Likewise, highly adaptive decisions improve responsiveness but may cause route oscillation when state information is delayed or incomplete. LEO routing should therefore be treated as a multi-objective, time-dependent optimization problem. Its performance can be assessed through end-to-end delay, throughput, packet-loss ratio, load-distribution fairness, route stability, and signaling overhead. This unified model provides the analytical basis for comparing topology-driven conventional routing with load- and QoS-aware adaptive mechanisms.

3. Classification Framework for Satellite Network Routing Technologies

The diversity of routing schemes developed for low Earth orbit satellite networks makes a coherent classification essential. Existing methods are often grouped according to implementation architecture, path-computation location, or algorithmic principle [10]. For example, routing may be described as centralized or distributed, single-path or multipath, deterministic or learning-based. Although these dimensions are useful, they do not directly reveal how a scheme responds to the fundamental tension identified in Section 2: orbital motion produces largely predictable topology variations, whereas traffic demand and resource availability change in a less regular manner. Accordingly, this paper classifies satellite routing technologies primarily by the information used to make forwarding decisions. Two major categories are distinguished: topology-driven conventional routing and state-driven adaptive routing.

3.1. Classification Basis and Analytical Dimensions

The proposed framework is organized around three questions. First, what network information determines the route? Second, on what time scale is that information updated? Third, which performance objective dominates the decision process? These questions provide a more consistent basis for comparison than the name of a specific algorithm. A distributed protocol, for instance, may still be topology-driven if it selects paths only from connectivity and propagation information. Conversely, a centrally calculated route can be adaptive when it incorporates current link loads, service priorities, or predicted traffic demand.

Topology information includes satellite positions, inter-satellite link availability, connectivity snapshots, propagation distance, and hop count. Much of it can be derived from orbital parameters and calculated before actual forwarding occurs. Traffic-state information, by contrast, covers queue occupancy, residual bandwidth, link utilization, packet loss, flow intensity, and congestion trends. Service-state information further describes application requirements, such as delay bounds, jitter tolerance, minimum throughput, reliability, and traffic priority. As the decision input expands from topology alone to traffic and service states, routing becomes more responsive to actual operating conditions. However, its measurement, signaling, and computational costs also increase.

Several secondary dimensions are employed within each category. In terms of control organization, a scheme may be centralized, distributed, or hierarchical. With respect to temporal operation, route computation can be event-triggered, periodically updated, or performed for a sequence of topology snapshots. Forwarding may rely on one path, several concurrent paths, or a primary route accompanied by backup alternatives. Finally, the optimization process can be model-based, heuristic, optimization-driven, or learning-assisted. These dimensions intersect rather than form mutually exclusive categories; hence, they are used to characterize individual techniques instead of defining the principal taxonomy.

3.2. Topology-Driven Conventional Routing

Topology-driven routing treats network reachability and geometric cost as the principal basis of path selection. Its central objective is to maintain valid routes despite continuous satellite movement, usually while minimizing hop count, propagation delay, or a static combination of link costs. Because orbital trajectories exhibit strong regularity, the observation period can be divided into a sequence of topology states. Routes are calculated for each state and installed when the corresponding interval begins. This snapshot-based treatment converts a continuously evolving constellation into several manageable static graphs.

Within this category, shortest-path routing constitutes the most direct approach. Link weights are assigned according to distance, propagation delay, or hop count, after which a graph-search algorithm obtains an end-to-end path. Virtual-topology methods pursue a different abstraction: logical nodes or links remain comparatively stable even though the physical satellites associated with them change. Such designs reduce the apparent frequency of topology updates and simplify routing management. Location-assisted or geometric schemes further exploit orbital coordinates and relative destination direction, allowing a satellite to select an appropriate next hop without maintaining complete global state. Meanwhile, hierarchical strategies divide a large constellation into domains, orbital planes, or logical regions, thereby limiting the scope of route computation and control-message exchange.

These mechanisms offer predictable behavior, moderate onboard complexity, and relatively low state-collection overhead. They are especially suitable when traffic is light or broadly distributed. Their limitation is equally clear. Since a route is selected mainly from nominal topology, many flows may converge on identical shortest paths, overloading a subset of inter-satellite links while other resources remain idle. A physically efficient route can therefore become operationally inefficient once queueing delay is considered [2].

3.3. State-Driven Adaptive Routing

State-driven adaptive routing supplements structural knowledge with observations of current or predicted network conditions. The path cost is no longer fixed solely by geometry; instead, it changes with queue length, channel utilization, residual capacity, loss probability, traffic class, or a combination of these variables. Traffic-aware schemes redirect flows away from congested links. Load-balancing methods distribute packets or sessions among multiple feasible paths, seeking to improve resource utilization and prevent regional bottlenecks. Multipath routing may also enhance resilience by maintaining alternatives before a link interruption occurs.

QoS-aware routing extends adaptation from network state to service intent. Rather than minimizing one universal metric, it applies differentiated constraints or weights. Delay-sensitive traffic may be assigned a short and lightly queued path, whereas high-throughput services can be directed toward routes with greater residual bandwidth. Reliability-critical flows may use stable links, redundant transmission, or protected backup paths. More recent optimization- and learning-assisted approaches attempt to infer complex relationships among topology, demand, and long-term performance; nevertheless, their practical value depends on computational affordability, training robustness, interpretability, and the availability of trustworthy state information.

Adaptation improves responsiveness, but it introduces new risks. State reports consume scarce bandwidth and may already be outdated when received. Excessive reaction to short-lived fluctuations can cause route oscillation, forwarding inconsistency, and packet reordering. Moreover, optimizing flows independently may shift rather than eliminate congestion. Effective adaptive routing therefore requires controlled update intervals, state aggregation, hysteresis, or stability constraints [6].

4. Conventional Routing Based on Topology and Shortest Paths

Conventional routing in satellite networks primarily determines forwarding decisions from relatively stable structural information, including satellite positions, inter-satellite links, orbital relationships, hop count, physical distance, and propagation delay. Unlike terrestrial networks, where topology changes are often treated as irregular failures or unexpected events, low Earth orbit satellite networks exhibit substantial regularity because their connectivity is governed by orbital motion. This predictability makes it possible to construct routing paths in advance and update them according to anticipated topology changes. Consequently, topology-driven routing remains an important foundation for satellite network design, particularly when the primary objectives are path reachability, low computational overhead, and operational stability.

4.1. Static Shortest-Path and Backup-Path Routing

The basic approach is to represent satellites as network nodes and inter-satellite links as connections between them. A routing algorithm then selects a path with the lowest accumulated cost between a source satellite and a destination satellite. Depending on the design objective, the cost may be defined by the number of forwarding hops, the physical length of the links, or the expected propagation delay. Classical shortest-path procedures, such as Dijkstra's algorithm and the Bellman–Ford algorithm, can be applied after the satellite topology has been established [2].

A minimum-hop path is attractive because it is simple to calculate and generally requires fewer forwarding operations. It is therefore suitable for systems with limited onboard processing capability. Nevertheless, hop count does not necessarily reflect communication quality. Two paths containing the same number of hops may differ considerably in link length, propagation delay, or transmission reliability. A distance-oriented path can reduce the physical transmission span and may improve delay performance, whereas a delay-oriented path more directly reflects the time required for end-to-end information delivery. The selection of a particular metric should therefore be consistent with the service objective and the characteristics of the satellite constellation.

A single shortest path, however, is vulnerable to link interruption. Satellite movement, obstruction, link degradation, or temporary equipment failure can invalidate a previously selected route. For this reason, conventional routing schemes often maintain several alternative paths. Backup paths may be selected according to their similarity to the primary route, their disjointness from it, or their ability to avoid vulnerable links and satellites. When the main path becomes unavailable, traffic can be transferred to an alternative route without initiating a complete network-wide computation. This mechanism improves route survivability and reduces the interruption caused by predictable topology changes.

The main limitation is that shortest-path routing optimizes structural distance rather than current network conditions. A path that is short in terms of hops or delay may pass through a heavily used satellite or a congested inter-satellite link. Thus, although the method provides a reliable baseline for path construction, it cannot by itself respond effectively to uneven traffic distribution.

4.2. Topology Snapshots and Virtual Topology

Because satellite connectivity changes continuously, calculating routes from instantaneous positions at every moment would impose considerable signaling and computational costs. A widely used solution is to divide network operation into a sequence of topology intervals. Within each interval, the physical topology is regarded as sufficiently stable, and routing decisions are computed from a representative topology snapshot [4]. At the boundary between two intervals, the routing information is updated to reflect the next predicted configuration.

This method transforms a continuously changing network into a series of manageable routing states. It reduces the frequency of route recomputation and allows forwarding tables to be prepared before the corresponding topology becomes active. The duration of an interval must be chosen carefully. If it is too long, the assumed topology may differ significantly from the actual link state, increasing the risk of invalid routes. If it is too short, the network may suffer from frequent table updates, signaling overhead, and route oscillation.

The virtual-topology concept extends this idea by grouping physically different but structurally similar network configurations into a common logical state [3]. Satellites may move relative to one another, yet their connectivity relationships can remain equivalent from the perspective of routing. By mapping these recurring configurations to a limited set of virtual topologies, the system can reuse routing rules instead of generating a completely new table for every physical position. This is particularly useful for regular constellations whose orbital motion follows predictable patterns.

Topology snapshots and virtual topologies offer three notable benefits. First, they exploit the deterministic component of satellite motion. Second, they simplify route management and reduce the amount of real-time control information required. Third, they facilitate synchronized routing-table updates across satellites. Their effectiveness, however, depends on accurate orbit prediction and reliable timing coordination. Unexpected link failures, atmospheric effects, or changes in gateway availability may cause the actual network state to diverge from the planned topology. Therefore, topology-based routing must retain mechanisms for local failure detection and temporary route repair.

4.3. Periodic Route Updating and Dynamic Adjustment

Periodic routing further incorporates the temporal characteristics of satellite networks. Routing tables are updated at predefined moments or when the network enters a new predicted topology state [5]. During most of the interval, satellites use stable forwarding rules; when a scheduled transition occurs, they replace the old rules with those associated with the next state. Compared with fully reactive routing, this approach avoids repeated global convergence and makes route behavior more predictable.

Dynamic adjustment can be introduced without changing the fundamental topology-driven framework. When a link disappears or a neighboring satellite becomes unreachable, local nodes may select a precomputed backup path, redirect packets through an adjacent orbital plane, or temporarily use a locally repaired route [7]. Such adjustments are especially valuable when the disruption is short-lived or limited to a small part of the constellation. They also reduce the need for immediate coordination among all satellites.

Nevertheless, periodic and locally adaptive updates involve a clear trade-off. Stable routing tables reduce control overhead, but they may respond slowly to sudden failures. More frequent updates improve responsiveness while increasing synchronization traffic and processing demand. In addition, repeated path changes can cause packet reordering, transient loops, or route oscillation if update timing is inconsistent. Practical systems therefore require safeguards such as synchronized transitions, temporary route holding, loop prevention, and controlled use of backup paths.

Overall, conventional topology-based routing provides a stable and computationally manageable basis for satellite networks. It makes effective use of orbital predictability, supports precomputed paths, and offers relatively low deployment complexity. Its weakness lies in the limited information used for decision-making: topology and distance can indicate whether a route is available and how long it may be, but they reveal little about queue occupancy, bandwidth consumption, traffic priorities, or emerging congestion. Accordingly, shortest-path and virtual-topology mechanisms should be regarded as the structural foundation of satellite routing. More advanced schemes can build upon this foundation by introducing traffic state and quality-of-service information, thereby combining predictable topology management with responsive network adaptation.

5. Adaptive Routing Oriented toward Traffic, Load, and Quality of Service

Topology-based routing can exploit predictable orbital motion to maintain reachability, yet topology information alone cannot describe the instantaneous operating condition of a satellite network. User demand is geographically uneven, traffic intensity varies across regions and time periods, and gateway distribution may concentrate flows on a limited number of inter-satellite links. Consequently, a path that is optimal from the perspective of hop count or propagation distance may perform poorly once queueing delay and resource contention are considered. Adaptive routing addresses this limitation by incorporating traffic characteristics, network load, and quality-of-service requirements into path selection. Its objective is no longer merely to identify an available short path, but to allocate limited network resources while sustaining acceptable service performance under changing conditions.

5.1. Load-Aware and Congestion-Avoidance Routing

Load imbalance arises from both the spatial distribution of users and the structural properties of a constellation. Densely populated areas generate more access traffic than oceans or sparsely inhabited regions, while diurnal activity causes regional demand to change over time. In addition, traffic destined for terrestrial networks tends to converge near gateways. When numerous shortest paths share the same satellites or links, these network elements may become bottlenecks even though substantial capacity remains available elsewhere.

Load-aware routing therefore evaluates paths using real-time or recently observed network conditions [6]. Relevant information may include link utilization, residual bandwidth, queue occupancy, packet loss, and congestion indications. A lightly loaded path can be preferred over a nominally shorter but congested route, thereby preventing excessive queue accumulation and improving overall resource utilization. Some schemes continuously adjust link costs according to measured load, whereas others trigger rerouting only after congestion exceeds a predefined threshold. The former responds rapidly but may generate frequent route changes; the latter offers greater stability, although its reaction to sudden traffic bursts can be slower.

The usefulness of load information depends strongly on its timeliness. Satellite states may change before measurements have been collected, disseminated, and processed. Decisions based on outdated reports can shift traffic toward a link that is no longer underutilized. Moreover, if many satellites respond simultaneously to the same congestion signal, flows may oscillate between several paths and create new hotspots. Practical designs should therefore combine smoothed measurements, hysteresis mechanisms, and minimum route-holding periods. Local congestion avoidance is often more feasible than frequent network-wide optimization because it restricts signaling and computation to the affected area.

5.2. Multipath Routing and Traffic Distribution

Multipath routing expands the available forwarding space by maintaining several feasible routes between communicating endpoints [7]. Instead of concentrating all packets on a single shortest path, the network distributes traffic across paths with different load levels or structural characteristics. This approach can increase aggregate throughput, utilize otherwise idle links, and reduce the impact of individual link failures. It is particularly beneficial in large constellations, where multiple inter-plane and intra-plane alternatives may exist.

Traffic distribution may operate at the flow level or the packet level. Flow-level allocation assigns each session to one path and preserves packet order, making it suitable for transport protocols that react adversely to reordering. Its ability to balance load is nevertheless limited when a few large flows dominate the traffic. Packet-level distribution achieves finer resource allocation, but differences in propagation and queueing delay can cause packets to arrive out of sequence. The resulting reordering may increase buffering demand and be misinterpreted as packet loss by upper-layer protocols. Thus, distribution granularity should be selected in accordance with service characteristics rather than purely according to link utilization.

Path diversity also requires careful control. Routes that share many satellites or links provide little additional resilience and may compete for the same constrained resources. By contrast, highly disjoint paths can improve robustness but may involve longer propagation distances. An effective multipath strategy should select alternatives that are sufficiently diverse while limiting excessive detours. It should also avoid unnecessary path switching, since frequent redistribution increases control overhead and makes network behavior difficult to predict.

5.3. Quality-of-Service-Aware Routing

Quality-of-service routing extends adaptive decision-making from network load to service-specific requirements [8]. Satellite networks carry heterogeneous traffic, including interactive communications, broadband data, remote sensing information, emergency messages, and delay-tolerant transfers. These services do not value network attributes equally. Real-time communication is sensitive to latency and delay variation, bulk data transfer depends more heavily on throughput, and safety-critical traffic requires high reliability and rapid recovery.

Accordingly, QoS-aware routing selects paths by considering several service constraints together [9]. Candidate routes may be screened according to available bandwidth, expected delay, loss conditions, reliability, and stability over the anticipated transmission period. Traffic classes can then receive differentiated treatment. Delay-sensitive flows may use shorter and less congested paths, whereas elastic traffic may be redirected through longer routes to release scarce capacity. During overload, admission control and priority scheduling can further prevent newly arriving low-priority traffic from degrading established critical services.

Nevertheless, satisfying multiple objectives introduces difficult trade-offs. A route with low propagation delay may offer limited residual capacity, while a highly reliable path may consume more hops and energy. Furthermore, strict QoS guarantees are challenging when links change with orbital movement and traffic conditions remain uncertain. Routing decisions should therefore consider not only present performance but also expected path lifetime and the cost of upcoming handovers. Excessively aggressive optimization may improve short-term metrics while causing route instability, signaling growth, and interrupted service.

Overall, adaptive routing complements rather than replaces topology-driven mechanisms. Load awareness improves congestion avoidance, multipath forwarding broadens resource utilization, and QoS constraints support differentiated services. These benefits, however, must be evaluated alongside state-collection overhead, onboard processing demand, route oscillation, and packet reordering. A practical architecture should use predicted topology and precomputed routes to preserve basic connectivity, while applying localized load sensing and QoS-based adjustment only where operational conditions require it. Such a hybrid approach combines the predictability of orbital dynamics with responsiveness to stochastic traffic, providing a more balanced basis for scalable satellite routing.

6. Conclusion

This paper has reviewed the principal routing mechanisms for low Earth orbit satellite networks under dynamic topology, uneven traffic distribution, constrained onboard resources, and differentiated service requirements. Conventional topology-driven approaches exploit predictable orbital movement to maintain connectivity and control propagation delay with relatively low implementation complexity. However, their limited awareness of real-time network conditions restricts performance under congestion and fluctuating demand. By contrast, adaptive routing incorporates traffic load, path diversity, and quality-of-service requirements, thereby improving resource utilization and service differentiation, although at the cost of additional signaling and computational overhead. Overall, these two categories should be regarded as complementary rather than mutually exclusive. Future satellite routing architectures should combine topology prediction and precomputed paths with timely state sensing and localized adaptation. Such integration can preserve routing stability while responding efficiently to traffic variations, link disruptions, and heterogeneous service demands, ultimately supporting scalable and reliable satellite network operation.

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