Model-Driven Distributed Routing in Satellite Constellations: DisCoRoute and Beyond

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DisCoRoute introduced model-driven distributed routing for satellite constellations by exploiting orbital geometry to approximate near-optimal paths with low onboard computation. Since its initial proposal, a growing body of work has extended this paradigm to new orbital regimes, sparse inter-satellite connectivity, cross-layer evaluation, and region-aware optimizations. This paper synthesizes these developments through a structured taxonomy spanning regimes, dynamics, connectivity models, and methodological scope, and highlights recent studies that use DisCoRoute as a benchmark. We conclude by outlining research directions toward operational routing, including resilience to failures, hybrid control, and end-to-end path selection in multi-shell architectures.

1 Introduction

The rapid deployment of large-scale satellite mega-constellations is reshaping the design space of space communication networks. Unlike traditional satellite systems, these constellations exhibit predictable orbital dynamics yet operate at unprecedented scales, rendering centralized routing approaches increasingly difficult to sustain. As a result, distributed routing strategies that exploit structural regularities of constellation topologies are emerging as a promising alternative.

Within the context of the MISSION project,[1] DisCoRoute introduced a model-driven approach to distributed routing that leverages orbital geometry to approximate optimal paths while maintaining low computational overhead. Since its introduction, the algorithm has evolved beyond its original formulation, inspiring a growing body of work that explores new orbital regimes, connectivity constraints, cross-layer interactions, and operational considerations.

This paper reviews the evolution of the DisCoRoute research line, largely enabled by the MISSION project, and organizes the resulting contributions into a structured taxonomy. By synthesizing these developments, we identify the key principles underpinning model-driven distributed routing and outline the challenges that must be addressed to transition from algorithmic feasibility toward operational deployment in future satellite networks.

[1] https://mission-project.eu/

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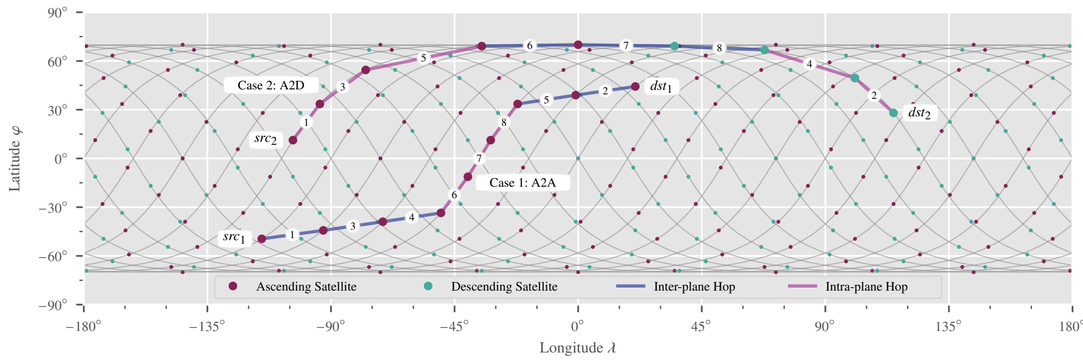

Figure 1: DisCoRoute algorithm: inter-plane hops are kept near high-latitude regions [13].

2 DisCoRoute: A Model-Driven Distributed Routing Paradigm

DisCoRoute is a distributed, model-driven routing algorithm designed for large-scale satellite mega-constellations with predictable orbital dynamics. Introduced by Stock et al. [13], the algorithm departs from classical shortest-path approaches by exploiting the geometric regularity of Walker-type constellations to compute forwarding decisions locally, without requiring global topology knowledge (see Figure 1).

At its core, DisCoRoute relies on an analytical estimation of the minimum hop count between satellites derived directly from orbital parameters. Rather than performing iterative graph searches, each node infers the direction of progress toward the destination using relative plane indices and intra-plane positioning. This enables near-optimal path selection while drastically reducing computational overhead.

The algorithm is inherently scalable: routing decisions depend only on local state and lightweight geometric models, making DisCoRoute particularly attractive for onboard execution where processing resources and energy budgets are constrained. Moreover, its distributed nature avoids the fragility and signaling overhead associated with centralized route computation.

Beyond its initial performance results, DisCoRoute established three key principles that have shaped subsequent research:

- **Geometry-aware routing:** orbital structure can be leveraged to approximate optimal paths.
- **Distributed decision-making:** global recomputation is not a prerequisite for efficient routing.
- **Hop-first optimization:** hop count often provides a better proxy for end-to-end delay than distance.

These properties position DisCoRoute not merely as a routing heuristic but as a foundational paradigm for model-driven networking in satellite constellations. The following section organizes the growing body of work building upon this paradigm into a structured taxonomy.

3 Taxonomy

Since its introduction, DisCoRoute has evolved from a geometry-aware distributed routing algorithm into a broader research line addressing increasingly challenging orbital regimes, connectivity constraints, and evaluation methodologies. Largely enabled by the MISSION project, this progression reflects a shift from foundational algorithm design toward system-level experimentation and topology-aware adaptations.

3.1 Chronological Evolution

The DisCoRoute research line was initiated in 2022 and reached experimental maturity by 2025, largely supported by the MISSION project. Since 2024, it has expanded toward new regimes and operational constraints.

Foundations (2022). DisCoRoute was originally proposed as a distributed, model-driven routing algorithm for LEO mega-constellations [13]. By leveraging orbital geometry and minimum-hop analytical models, it demonstrated that near-optimal routing decisions could be computed locally without centralized path precomputation. This work established three key principles that underpin subsequent research: geometry-aware routing, distributed decision-making, and hop-first optimization.

Experimental Maturity (2023–2025). The development of a benchmarking framework by Ohs [10] marked a methodological turning point, transforming DisCoRoute from a conceptual algorithm into an experimentally reproducible discipline. Building upon this effort, FLoRaSat 2 [5, 6] introduced an end-to-end constellation simulator capable of jointly evaluating access and routing layers, enabling cross-layer performance analyses under congestion, failures, and dynamic topology conditions.

Regime Expansion (2024). Within the context of the ESA HANDING-OVER project [7], Ottaviani [11] conducted the first systematic evaluation of DisCoRoute in VLEO environments. The study revealed structural inefficiencies in high-inclination constellations, particularly near the poles, motivating the development of geometry-aware heuristics such as *Targeted for Arctic and Antarctic Tracking* (TAAT) to mitigate excessive detours.

Topology-Constrained Routing (2025). Benso [2] extended the paradigm to sparse connectivity architectures by introducing DisCo3T, a distributed algorithm tailored for three-terminal (3T) inter-satellite links, within the ESA HANDING-OVER project [7]. The same work also introduced analytical hop-count models for intermittent horizontal connectivity and seam-aware Walker-Star geometries, indicating that model-driven distributed routing remains viable under strong structural constraints.

Region-Aware Optimization (2025). Ottaviani et al. [12] further showed that constellation geometry influences routing performance more significantly than altitude alone. Particularly, the study showed that performance is more variable in constellations with high inclination and a limited number of orbital planes. Their PolarDisCo heuristic exploits low-cost polar links to reduce latency, highlighting the importance of spatially localized routing strategies.

Algorithmic Consolidation (2025). Benso et al. [3] formalized the DisCo3T approach in a dynamic simulation setting, achieving near-optimal latency while reducing computational cost by nearly two orders of magnitude relative to Dijkstra-based routing. This result provides strong evidence for the onboard feasibility of distributed routing in next-generation VLEO constellations.

3.2 Taxonomy Dimensions

The reviewed works can be organized along several orthogonal dimensions:

- **Orbital regime:** from LEO to VLEO, reflecting increasing topology volatility.
- **Network dynamics:** progressing from predictable geometries to highly time-varying constellations.
- **Connectivity model:** evolving from dense four-terminal meshes to sparse directional architectures.
- **Methodological scope:** transitioning from algorithm design to tooling and cross-layer simulation.
- **Spatial awareness:** moving toward region-aware routing strategies optimized for polar environments.

Summarized in Table 1, these dimensions illustrate a broader shift from routing feasibility toward routing robustness under structural and operational constraints.

Table 1: Taxonomy of DisCoRoute-based research.

Work	Year	Regime	Dynamics	Topology	Method	Evaluation
Stock et al. [13]	2022	LEO	Moderate	4T Walker-Delta	Distributed hop-based routing (DisCoRoute)	Large-scale constellation simulation
Ohs [10]	2023	LEO	Moderate	Walker-Star / Delta	Benchmarking framework and simulation tooling	Discrete-event experiments with failures and congestion
Choquenaira-Florez et al. [5, 6]	2025	LEO	Moderate	Cross-linked constellations	End-to-end simulator with joint MAC–routing evaluation	System-level experiments at constellation scale
Ottaviani [11]	2024	LEO+VLEO	High	4T Walker-Delta	Geometry-aware heuristic (TAAT)	Sensitivity analysis over altitude and inclination
Benso [2]	2025	VLEO	Very High	3T / 4T	DisCo3T + analytical hop models	Dynamic simulations with temporal routing analysis
Ottaviani et al. [12]	2025	LEO+VLEO	High	4T Walker-Delta	Region-aware routing (PolarDisCo)	Large-scale delay distribution study
Benso et al. [3]	2025	VLEO	Very High	3T directional	Distributed routing under sparse connectivity	Time-varying constellation simulations

3.3 Other Related Works

Beyond the works directly supported by MISSION, several recent studies use DisCoRoute as a benchmark when evaluating new routing strategies in satellite constellations. This trend further reinforces the algorithm's role as a baseline for distributed routing in predictable orbital topologies.

Chen et al. [4] propose an explicit analytic shortest-distance-path algorithm that exploits constellation regularity. In their related work discussion, DisCoRoute is identified as an approximate distributed solution that leverages high-latitude inter-plane links to reduce path length.

Similarly, Zhang et al. [14] introduce GRLR, a grid-based low-latency routing method for mega-constellations. DisCoRoute is used as a benchmark for distributed strategies in topology-aware routing, with the aim of reducing computational overhead relative to classical shortest-path algorithms.

Gao et al. [8] explore intelligent routing mechanisms driven by adaptive decision processes. In this context, DisCoRoute serves as a representative geometry-aware distributed heuristic, enabling the authors to position their approach relative to lightweight onboard routing solutions.

Barbier et al. [1] investigate routing optimization opportunities in structured LEO networks and reference DisCoRoute among topology-exploiting algorithms that approximate shortest paths while maintaining low computational complexity.

Finally, the resiliency study by Esswein et al. [9] evaluates constellation reachability under compromised nodes using a Walker-Delta testbed. DisCoRoute is highlighted as a location-aware routing approach that prioritizes inter-plane hops near the poles to approximate shortest paths with reduced computation.

Takeaway. Collectively, these works suggest that DisCoRoute is increasingly treated not merely as a standalone routing proposal but as a methodological baseline for distributed, geometry-aware routing in satellite constellation research.

4 Research Directions

Beyond individual contributions, the taxonomy reveals a clear scientific trajectory:

- **Feasibility:** distributed routing is achievable at the constellation scale.

- **Reproducibility:** standardized tooling enables rigorous comparisons.
- **System integration:** cross-layer effects must be considered.
- **Structural adaptation:** routing must accommodate sparse and directional connectivity.
- **Spatial optimization:** localized strategies improve performance in geometrically distorted regions.

Taken together, these results suggest that distributed, model-driven routing is a scalable paradigm for future constellation architectures.

4.1 Methodological and Analytical Extensions

Despite the recent developments, several open research challenges remain.

Stronger optimality baselines. While prior evaluations typically compare against shortest-path routing, a systematic assessment using both hop-based and distance-based variants of Dijkstra would enable a clearer quantification of suboptimality and computational gains. Incorporating heuristic search methods such as A* could further contextualize the trade-off between optimality and onboard feasibility.

Model sensitivity and accuracy. DisCoRoute relies on onboard orbital parameters to analytically estimate minimum-hop paths. However, the sensitivity of these models to parameter uncertainty, ephemeris aging, or reduced numerical precision has not yet been thoroughly characterized.

Formal complexity analysis. Although empirical results consistently demonstrate substantial runtime reductions relative to centralized algorithms, a formal asymptotic analysis would clarify the computational scaling of distributed routing strategies.

4.2 Toward Operational Routing

Translating these approaches into operational deployments introduces additional challenges.

Resilience to failures and congestion. Future extensions should incorporate adaptive link selection driven by local observations or network feedback, enabling routing decisions that account for failed or congested links.

Hybrid distributed–centralized control. Despite the advantages of decentralization, operators may require policy-driven constraints, such as avoiding satellite eclipses, protecting energy-limited nodes, or steering traffic away from congested regions. Investigating hybrid architectures that combine distributed decisions with centralized orchestration represents a promising research avenue.

Entry and exit point awareness. Current formulations primarily focus on inter-satellite forwarding. Extending the model to explicitly account for paths to and from user terminals or ground stations would improve the realism of end-to-end routing. This is particularly relevant in multi-shell constellations, where selecting appropriate ingress and egress layers introduces an additional dimension of optimization.

Outlook. Collectively, these directions point toward a next generation of distributed routing algorithms that are not only geometry-aware but also resilient, policy-compliant, and operationally grounded. Advancing along these axes will be key to supporting the increasing scale, heterogeneity, and autonomy of future satellite networks.

5 Conclusions

This paper reviewed the evolution of DisCoRoute as a model-driven distributed routing paradigm for satellite constellations. The taxonomy highlights a shift from feasibility to operational viability through tooling, cross-layer evaluation, VLEO regimes, sparse connectivity, and region-aware adaptations. DisCoRoute's growing use as a benchmark further signals the maturation of geometry-aware distributed routing. Future work should prioritize resilience, hybrid control, and end-to-end integration.

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References

[1] Louis Barbier, Oana Hotescu, Jérôme Lacan & Emmanuel Lochin (2026): *Unlocking Resilience and Load Balancing: Toward Hop-By-Hop Routing for LEO Mega-Constellations*. In *IEEE Consumer Communications & Networking Conference*, doi: `10.1109/CCNC65079.2026.11366301`.

[2] Nicolò Benso (2025): *Routing Algorithms for VLEO Constellations*, Master's Degree Thesis. Politecnico di Torino, Turin, Italy. Available at `https://webthesis.biblio.polito.it/36476/`. Master's Degree in Communications Engineering. Supervisors: Roberto Garello, Juan Andres Fraire, Alessandro Compagnoni.

[3] Nicolò Benso, Alessandro Compagnoni, Gregory F Stock, Juan A Fraire, Gabriel Maiolini Capez, Camilla Ottaviani, Daniel Gaetano Riviello, Giacomo Verardo, Mirca Gargiulo, Leonardo Ospizio, et al. (2025): *Distributed On-Demand Routing for VLEO Constellations with 3-Terminal Inter-Satellite Links*. In *2025 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, IEEE, pages 1–7, doi: `10.23919/SoftCOM66362.2025.11197383`.

[4] Quan Chen, Lei Yang, Yong Zhao, Yi Wang, Haibo Zhou & Xiaoqian Chen (2024): *Shortest path in LEO satellite constellation networks: An explicit analytic approach*. *IEEE Journal on Selected Areas in Communications*. 42(5), pages 1175–1187, doi: `10.1109/JSAC.2024.3365873`.

[5] Alexander Y Choquenaira-Florez, Benoit Coeugnet, Robin Ohs, Juan A Fraire & Hervé Rivano (2025): *FLoRaSat 2: Simulating Cross-Linked Direct-to-Satellite IoT LEO Constellations with Joint Access and Routing Evaluation*. *International Journal of Satellite Communications and Networking*, doi: `10.22541/au.175647870.00758886/v1`.

[6] Alexander Y Choquenaira-Florez, Robin Ohs, Juan A Fraire & Hervé Rivano (2025): *FLoRaSat 2: Simulating Cross-Linked Direct-to-Satellite IoT LEO Constellations*. In *2025 12th Advanced Satellite Multimedia Systems Conference and the 18th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, IEEE, pages 1–8, doi: `10.1109/ASMS/SPSC64465.2025.10946025`.

[7] European Space Agency (2025): *HANDING-OVER: Handover, Data Routing and Radio Resource Management for Very Low Earth Orbit (VLEO) Broadband Constellations*. ESA Connectivity & Secure Communications archive. Available at `https://connectivity.esa.int/archives/projects/handingover`. Status: Ongoing; Status Date: 30 Jan 2025.

[8] Ya Gao, Qihua Huang, Ke Wang, Wenliang Lin, Heng Kang & Yicheng Liao (2025): *Intelligent Hierarchical Routing Strategy Based on Regional Division for Large-Scale LEO Satellite Constellations*. In *2025 IEEE/CIC International Conference on Communications in China (ICCC Workshops)*, IEEE, pages 1–6, doi: `10.1109/ICCCWorkshops67136.2025.11148142`.

[9] Alexander Kedrowitsch, Jonathan Black & Daphne Yao (2024): *Resilient routing for low Earth orbit mega-constellation networks*. In *Proceedings of the NDSS Workshop on Space Security (SpaceSec), San Diego, CA, USA*. Available at `https://www.ndss-symposium.org/wp-content/uploads/spacesec2024-41-paper.pdf`.

[10] Robin Ohs (2023): *Routing in Low-Earth Orbit Constellations: A Performance Comparison*, Master's thesis. Saarland University, Saarbrücken, Germany. Available at `https://thesis.robinohs.dev/thesis.pdf`. Masterarbeit, Dependable Systems and Software, Saarland Informatics Campus.

[11] Camilla Ottaviani (2024): *Routing Strategies for LEO and VLEO Mega-Constellations: Performance Evaluation and Enhancements*, Master's Degree Thesis. Politecnico di Torino, Turin, Italy. Available at `https://webthesis.biblio.polito.it/33042/`. Master's Degree in Communications and Computer Networks Engineering.

[12] Camilla Ottaviani, Alessandro Compagnoni, Juan A Fraire, Giacomo Verardo, Gabriel Maiolini Capez, Daniel Gaetano Riviello, Gregory Stock, Carla Fabiana Chiasserini & Roberto Garello (2025): *Advanced Routing Strategies for LEO and VLEO Constellations: Ensuring Polar Coverage*. In *2025 12th Advanced Satellite Multimedia Systems Conference and the 18th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, IEEE, pages 1–8, doi: `10.1109/ASMS/SPSC64465.2025.10946062`.

[13] Gregory Stock, Juan A Fraire & Holger Hermanns (2022): *Distributed on-demand routing for LEO mega-constellations: A starlink case study*. In *2022 11th Advanced Satellite Multimedia Systems Conference and the 17th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, IEEE, pages 1–8, doi: `10.1109/ASMS/SPSC55670.2022.9914716`.

[14] Senbai Zhang, Aijun Liu, Chen Han, Xin Xu, Xiaohu Liang, Kang An & Yunyang Zhang (2024): *Grlr: Routing with graph neural network and reinforcement learning for mega leo satellite constellations*. *IEEE Transactions on Vehicular Technology*, doi: `10.1109/TVT.2024.3471658`.