The Evolution of Uncertainty-Aware DTN Routing: MISSION-Driven Advances

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Space and satellite networks are traditionally modeled using deterministic contact plans, yet operational systems routinely deviate from these predictions due to environmental effects, hardware faults, and operational decisions. These deviations motivate uncertainty-aware routing, where forwarding decisions explicitly account for probabilistic connectivity and partial observability. This article synthesizes the evolution of uncertainty-aware routing in delay-tolerant networks (DTNs), a research direction initiated in 2018 and significantly advanced through the international collaboration fostered by the MISSION project. We introduce a multi-dimensional taxonomy that classifies existing approaches according to their uncertainty assumptions, replication strategies, solution techniques, failure models, and communication semantics. Our synthesis highlights a clear shift from deterministic scheduling toward decision-theoretic formulations, scalable statistical synthesis, learning-based methods, and online planning under dependent failures. At the same time, it exposes persistent gaps between modeling fidelity and deployability, particularly for large-scale space systems. By consolidating early foundations with the methodological expansion enabled by MISSION, this paper clarifies the emerging design space of uncertainty-aware routing and outlines key directions for building dependable and resilient space communication infrastructures.

1 Introduction

Space networks operate under intermittent connectivity, long propagation delays, and tightly constrained communication windows. Delay-Tolerant Networking (DTN) addresses these conditions through store-carry-forward communication guided by a *contact plan* that predicts future communication opportunities.

Although orbital dynamics enable reasonably accurate forecasts, operational systems rarely behave deterministically. Contacts may fail, degrade, or shift due to environmental effects, interference, or operational decisions. Routing strategies that assume perfect schedules can therefore misallocate resources, forward bundles toward nonexistent links, or trigger inefficient replication.

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These challenges motivate *uncertainty-aware* routing, in which contacts are modeled probabilistically and decisions account for partial observability. This paradigm bridges the gap between scheduled DTNs—where future connectivity is assumed reliable—and opportunistic networks that make no temporal assumptions. By retaining a time-indexed structure while relaxing determinism, uncertain DTNs better reflect modern space and satellite systems.

Reasoning in uncertain DTNs requires *formal analysis*: routing decisions can be cast as decision processes (e.g., MDPs and POMDPs), enabling principled reasoning about delivery probability, resource usage, and robustness under specified failure assumptions through techniques such as probabilistic model checking and sampling-based synthesis. This perspective aligns with the objectives of the MISSION project,[1] which investigates model-based design and verification techniques for dependable space systems and provides the scientific context for this work.

This paper synthesizes the emerging design space of uncertainty-aware routing. We trace its evolution within the context of the MISSION project, introduce a unified taxonomy, map existing approaches to their tooling and evaluation practices, and identify open research directions toward dependable large-scale space networks.

2 The Evolution of Uncertainty-Aware Routing in MISSION

Research on routing in Delay-Tolerant Networks (DTNs) under uncertain contact plans emerged in response to the growing gap between deterministic contact-graph assumptions and the realities of operational space systems. Early DTN routing protocols, most notably Contact Graph Routing (CGR), assume perfectly known and reliable contact schedules and are optimal only under this idealized setting [5]. However, empirical studies soon demonstrated that even modest levels of contact uncertainty can significantly degrade performance [7, 8], motivating the need for principled uncertainty-aware routing models.

The first systematic formalization of uncertainty-aware DTN routing dates back to 2018, with foundational work conducted at the Digital Communications Laboratory of the Universidad Nacional de Córdoba (UNC), Argentina. The BRUF framework [11, 13] introduced a Markov Decision Process (MDP) formulation of DTN routing under probabilistic contact failures, establishing delivery probability maximization as a formal optimization objective and providing exact solutions via probabilistic model checking. This work marked a shift from heuristic robustness toward decision-theoretic reasoning in space DTNs.

Building on these foundations, the line of research was significantly extended in 2021 with the introduction of RUCoP [12], which generalized BRUF to multi-copy routing and clarified the structure and scalability limits of optimal policies under uncertain contact plans. The same work also proposed practical local-information heuristics (CGR-UCoP and L-RUCoP) to bridge the gap between global optimality and deployable routing decisions, thereby anchoring uncertainty-aware routing within realistic DTN constraints.

A major inflection point for this research direction was the launch of the *MISSION* project (Marie Skłodowska-Curie RISE, Grant No. 101008233) on October 1, 2021. MISSION fostered sustained scientific exchange between UNC—now expanded through the Dependable Systems Group (DSG) at FAMAF—and European partners, most notably the University of Twente (Netherlands) and Saarland University (Germany), accelerating the development of richer uncertainty models and scalable solution techniques.

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

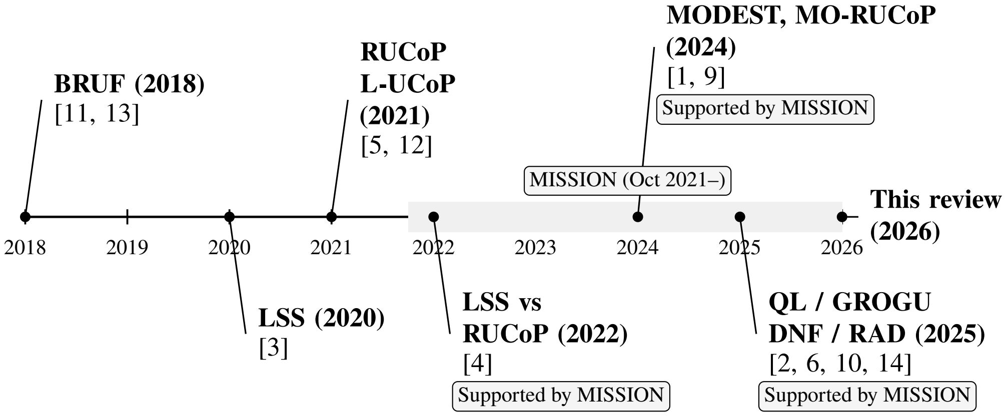

Figure 1: Timeline of uncertainty-aware DTN routing and its consolidation within MISSION.

This collaboration enabled the exploration of complementary approaches based on alternative solution paradigms. Lightweight Scheduler Sampling (LSS) [3, 4] introduced statistical model checking as a scalable mechanism for synthesizing distributed routing policies under uncertainty, later consolidated and operationalized through the MODEST toolset [1]. More recently, learning-based approaches—including tabular Q-learning [2] and deep reinforcement learning with graph neural networks (GROGU) [10]—have demonstrated the potential of data-driven methods to cope with partial observability and topology variability.

More recent advances include multi-objective optimization (MO-RUCoP) [9], dependent failure models formulated as POMDPs (DNF) [14], and dynamic replication strategies (RAD) [6]. As of 2026, MISSION remains active and continues to shape the research agenda in uncertainty-aware DTN routing, culminating in a dedicated workshop co-located with ETAPS 2026 (`https://mission-project.eu/etaps2026/`).

Figure 1 presents the overall timeline and shows that uncertainty-aware DTN routing did not evolve as isolated proposals, but as a cumulative research program that accelerated after the launch of MISSION.

3 Taxonomy of Uncertainty-Aware Routing

Existing approaches differ primarily in how they represent uncertainty, manage bundle copies, and compute forwarding policies. To make these design choices explicit, we classify the literature along five largely orthogonal dimensions.

The first dimension captures the *uncertainty model and observability*, distinguishing whether contacts are assumed deterministic or probabilistic, whether failures are independent or correlated, and whether routing decisions are made with global knowledge of the network state or only local observations. The second dimension concerns *copy management*, ranging from single-copy forwarding to statically bounded multi-copy routing and, more recently, exploratory forms of dynamically adapting the number of copies at runtime. The third dimension characterizes the *solution strategy*, spanning exact optimization via Markov decision processes, heuristic approximations, statistical synthesis, learning-based methods, and online planning under partial observability. The fourth dimension specifies the *failure granularity* captured by the model, from deterministic contact plans and binary contact failures to node-level failures that induce correlated disruptions across multiple links. Finally, the fifth dimension describes the assumed *communication semantics*, in particular whether transmissions are acknowledged—allowing precise copy conservation through custody transfer—or unacknowledged, as in deep-space settings where feedback

Table 1: Taxonomy of routing approaches for uncertain DTNs.

Approach	**Uncertainty & Observability**	**Copy Management**	**Solution Strategy**	**Failure Model**	**Comm. Model**	**Ref.**
CGR	(1a) None	(2a) Single	Dijkstra	(4d) None	N/A	[5]
BRUF	(1b) Global	(2a) Single	(3a) Optimal	(4a) Contact	(5a) Ack.	[11, 13]
RUCoP	(1b) Global	(2b) Static	(3a) Optimal	(4a) Contact	(5a) Ack.	[12]
MO-RUCoP†	(1b) Global	(2b) Static	(3a) Optimal, MO	(4a) Contact	(5a) Ack.	[9]
L-RUCoP	(1c) Local	(2b) Static	(3b) Heuristic	(4a) Contact	(5a) Ack.	[12]
CGR-UCoP	(1c) Local	(2b) Static	(3b) Heuristic	(4a) Contact	(5a) Ack.	[12]
LSS	(1c) Local	(2b) Static	(3c) Statistical	(4a) Contact	(5a/b) Both	[1, 3, 4]
QL	(1c) Local	(2b) Static	(3d) Learning	(4a) Contact	(5a) Ack.	[2]
GROGU	(1c) Local	(2b) Static	(3d) Learning	(4a) Contact	(5a) Ack.	[10]
RAD†	(1c) Local	(2c) Dynamic	(3b) Heuristic	(4a) Contact	(5a) Ack.	[6]
DNF	(1d) Local+Dep.	(2a) Single	(3e) Online	(4c) Node	(5a) Ack.	[14]

† Exploratory approach requiring further validation.

delays are prohibitive.

Together, these dimensions expose the modeling assumptions underlying each routing approach and clarify how choices about uncertainty, information, and failure semantics directly affect implementability, scalability, and achievable performance.

Table 1 summarizes this design space and highlights the progression from deterministic schedulers to probabilistic optimization, statistical synthesis, learning-based methods, and online decision processes. The taxonomy reveals a key trend: routing is shifting from static planning toward adaptive strategies that reason under incomplete knowledge.

4 Tooling and Evaluation Practices

Table 2 maps each surveyed work to its tooling dependencies, optimization objective, and the additional metrics reported in experimental evaluations. *Optimized* denotes the objective explicitly maximized by the method, whereas *Evaluated* lists complementary metrics reported but not directly optimized.

A heterogeneous ecosystem supports this research area. Probabilistic model checkers such as PRISM and Storm enable optimal policy synthesis, while MODEST supports statistical verification and reinforcement learning workflows. Simulation platforms—including DtnSim—and modern ML frameworks further facilitate empirical validation.

Despite this progress, reproducibility remains uneven due to fragmented tooling. To mitigate this, a companion artifact provides reference implementations spanning optimal, statistical, learning-based, and online routing strategies.[2]

5 Open Research Directions

As space networks scale toward constellation-class deployments, routing must transition from static planning to adaptive decision-making under structured uncertainty. The taxonomy highlights several

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[2] `https://doi.org/10.5281/zenodo.18507793`

Table 2: Tooling and evaluation metrics per surveyed work.

Ref.	Approach	Tooling	Optimized	Evaluated
[7]	CGR analysis	DtnSim	–	DR, rerouting, availability
[8]	CGR ext.	DtnSim	Del. time	DR, EE, buffer occ., E2E, HC
[13]	BRUF	PRISM	SDP	E2E
[11]	BRUF	PRISM, DtnSim	SDP	DR, EE, time, memory
[3]	LSS	MODEST	SDP	Time, schedulers sampled
[12]	RUCoP	RUCoP solver, PRISM	SDP	Time, memory
[9]	MO-RUCoP	MO-RUCoP solver	SDP, Del. time, EE	Time, memory
[4]	RUCoP vs LSS	MODEST, RUCoP solver	SDP	Time, memory, scalability
[2]	QL	MODEST, RUCoP solver	SDP	Time, memory, Q-table size
[10]	GROGU	PyTorch, PyG	SDP	Time, generalization
[6]	RAD	JuliaPOMDP, DtnSim	SDP	DR, EE, E2E, HC, time, memory
[14]	DNF	JuliaPOMDP, DtnSim	SDP + delay	DR, EE, E2E, HC, time, memory

Abbreviations: DR (delivery ratio), EE (energy efficiency), E2E (end-to-end delay), and HC (hop count).

research frontiers for uncertainty-aware DTN routing.

Adaptive replication. Most approaches rely on static copy budgets, leaving dynamic strategies largely unexplored. Preliminary work such as the Risk-Aware Duplication (RAD) model suggests that belief-driven replication could improve robustness while preserving scarce resources.

Richer failure models. Contact-level uncertainty dominates current studies, yet node failures, correlated disruptions, and environment-driven effects remain underrepresented.

Scalability. Exact optimization struggles with constellation-scale networks, motivating approximate solvers, hierarchical abstractions, and learning-based generalization.

Integrated evaluation. Future work should jointly consider delivery guarantees, latency, and resource efficiency to better capture operational trade-offs.

6 Conclusion

Uncertainty-aware routing is emerging as a foundational capability for dependable space networking. By structuring prior work into a coherent taxonomy and exposing key methodological gaps, this paper clarifies the transition from deterministic scheduling toward adaptive, probabilistic decision-making. The MISSION project acted as a catalyst, evolving early decision-theoretic formulations into a broader ecosystem spanning scalable synthesis, learning-based methods, and online routing techniques. Continued progress will depend on scalable algorithms, realistic failure models, and reproducible experimentation—essential ingredients for enabling the next generation of resilient space communication infrastructures.

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