Adaptive Scheduling for Hybrid RF/Optical Space Communications under Uncertainty: A Reinforcement Learning Approach

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Abstract- Future NASA missions will generate increasing volumes of science and operational data, creating a growing need for communication systems that can deliver mission-critical information reliably under dynamic and uncertain conditions. Hybrid RF/optical architectures are especially promising because they combine the robustness of RF links with the high-capacity potential of optical links, but their effective use requires adaptive scheduling under time-varying link quality, intermittent contact opportunities, and changing traffic demands. To address this challenge, this project develops a reinforcement learning (RL)-enabled adaptive scheduling framework for hybrid RF/optical space communications under uncertainty. The proposed research will develop a simulation environment, implement an RL-based scheduler that dynamically selects transmission actions based on evolving network conditions and mission-oriented objectives, and benchmark the learned policy against conventional baseline methods. Expected outcomes include a proof-of-concept prototype, preliminary results for future external funding proposals, and strengthened DSU-led research capacity, collaboration, and student training in NASA-relevant communication technologies.

1. Narrative

1.1. Research Question

Future NASA missions increasingly depend on communication systems that can return mission-critical science data under dynamic and uncertain operating conditions. Hybrid RF/optical architectures are especially promising because they combine the robustness of RF links with the high-capacity potential of optical links. This opportunity is already reflected in NASA's recent development efforts; for example, at the Goldstone complex in California, Deep Space Station 13 was retrofitted with an optical terminal and demonstrated simultaneous reception of RF and laser signals from deep space [1]. However, their effective use remains challenging because contact opportunities, link quality, and traffic urgency can vary substantially over time, while severe optical degradation can jeopardize timely delivery of high-priority data. Existing scheduling approaches are often static or primarily optimization-based, and prior learning-based methods have not adequately addressed risk-aware scheduling for mission-critical data delivery in hybrid RF/optical settings [5 - 7]. These challenges motivate the central research question of this project: *How can we enable adaptive and risk-aware scheduling of mission-critical data over hybrid RF/optical space communication links under uncertain and time-varying contact and channel conditions?* To address this question, this project develops a reinforcement learning (RL)-based scheduling framework that learns to adapt transmission decisions online to evolving communication conditions while incorporating risk-aware mechanisms to reduce severe deadline shortfalls for high-priority science data.

1.2. Theoretical Grounding

System Model. We consider a hybrid RF-laser communication system supporting science return mission over discrete epochs $t = 1, \ldots, T$. At each epoch, the scheduler allocates data volume $x_k^{rf}(t) \geq 0$ over RF and $x_k^{op}(t) \geq 0$ over the laser link, subject to time-varying communication opportunities and link capacities. The RF link provides relatively dependable but limited-rate service, whereas the optical link offers high-capacity transmission but is vulnerable to environmental and operational uncertainty.

Risk Metric. We define the total data packet loss as L, which is depending on the scheduler and laser link quality. To achieve risk-averse performance while retaining stochastic information, we adopt the conditional value-at-risk (CVaR) of L, a widely used tail-risk measure in financial risk management. For a confidence level $\beta \in [0,1)$, $\mathrm{CVaR}_\beta(L)$ captures the expected loss in the worst $(1-\beta)$ tail events. Directly computing $\mathrm{CVaR}_\beta(L)$ via is nontrivial. Following [4], $\mathrm{CVaR}_\beta(L)$ can be computed efficiently using samples of stochastic laser delivery process.

Problem Formulation. We define the mission utility U as the total priority-weighted on-time delivery. We will compute $\{x_k^{rf}(t), x_k^{op}(t)\}$ by solving:

$$\max_{\boldsymbol{x}} \mathbb{E}[U] \quad \mathrm{s.t.} \quad \mathrm{CVaR}_\beta(L) \leq \tau,$$

together with capacity constraints. Here, $\tau \geq 0$ is a mission-defined risk tolerance that reflects how much worst-case degradation the mission is willing to accept. The CVaR-based constraint is used to explicitly control the tail risk of missed deadlines under unfavorable link qualities [2, 3], enabling schedules that are robust rather than optimized only for average data delivery. As shown in Fig. 1, building on this formulation, the proposed research is organized into two following tasks via a RL approach.

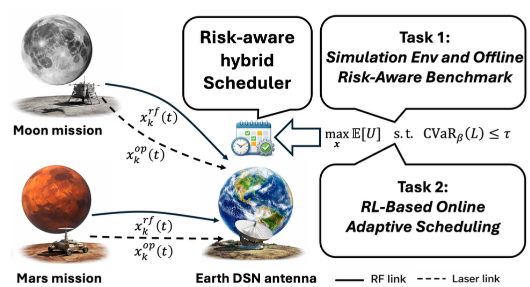

Fig. 1. Proposed research tasks.

1.3. Research Plan

Task 1: Simulation Environment and Offline Risk-Aware Benchmark. This task will develop a mission-driven simulation environment for hybrid RF/optical space communications under uncertainty. The environment will capture key operational features of NASA-relevant science-return scenarios, including time-varying contact opportunities, heterogeneous RF and optical link conditions, mission data classes with different priorities and deadlines, and uncertain optical delivery outcomes under varying operating conditions. It will also represent the interaction between current transmission decisions and future

delivery feasibility, so that both expected mission utility and deadline-sensitive risk can be evaluated in a controlled and reproducible setting. This simulation environment will serve as the common experimental foundation for the project: it will support the implementation of the offline risk-aware benchmark in Task 1 and provide the training and evaluation platform for the RL-based online adaptive scheduler in Task 2.
Task 2: RL-Based Online Adaptive Scheduling. Building on the simulation environment established in Task 1, this task will develop an RL-based scheduler for online hybrid RF/optical operations under uncertain and time-varying communication conditions. Although RL has been used in prior studies for adaptive scheduling in laser communications, existing methods do not provide risk-averse control for mission-critical data delivery based on hybrid RF-laser settings [8 - 10]. Specifically, we reformulate the problem as a *Markov Decision Process (MDP)*. At each decision epoch t, the *state* includes the current RF and link capacities. The *action* specifies a feasible allocation $\{x_k^{rf}(t), x_k^{op}(t)\}$ across priority classes subject to the capacity constraints. The actual optical delivery in each epoch depends on the stochastic delivery efficiency $\eta(t)$, which is not known perfectly a priori; it is revealed online only after communication conditions are realized. The *reward* will be aligned with mission utility, while risk will be assessed by evaluating $\mathrm{CVaR}_\beta(L)$ relative to the tolerance threshold τ. The outcome from this trust is an online scheduling policy that can exploit favorable revealed laser conditions when they occur and rapidly adjust allocations when degradations are observed. Learned policies will be benchmarked against the offline risk-constrained optimization solutions from Task 1. The table below shows the timeline of each task accomplished and milestones during this project.

Task	Month 1-6		Month 7-12		Milestones
Task 1: Simulation Environment and Offline Risk-Aware Benchmark					Problem formulation completed; Risk-aware routing policy developed
Task 2: RL-Based Online Adaptive Scheduling					Online adaptive policy developed; comparison against baselines

Table 1. Project schedule and milestones.

1.4. NASA Collaboration

This project will be supported by collaboration with *Mahmooda Sultana (NASA GSFC)*, whose expertise in planetary science instrumentation, space instrument systems, and science-operations-driven technology development will help align the proposed work with realistic NASA mission needs. Dr. Sultana is currently leading the Multifunctional Nano sensor Platform and Quantum Dot Spectrometer instrument development efforts and is developing the ScienceCraft for Outer Planet Exploration (SCOPE) mission architecture. Her involvement will strengthen the project's relevance to mission-critical science return, operational reliability, and future NASA space communication systems. It is noted that an undergraduate student from College of Agriculture, Science and Technology at DSU has interned at NASA GSFC each summer for the past three years.

1.5. Significance of Larger Project

The proposed seed project is designed as a foundational step toward a larger research program on autonomous, resilient, and mission-aware space communication systems for future NASA missions. While the seed effort focuses on hybrid RF/optical scheduling under uncertainty, it has significant potential to extend beyond the immediate pilot study. Specifically, in the larger project, the proposed framework can be extended in several important directions, including multi-node and multi-mission scheduling, richer contact and channel uncertainty models, tighter integration with mission priorities and science-return requirements, and more advanced autonomous decision-making for space communication operations. More broadly, the project advances a long-term vision in which AI-enabled scheduling supports reliable science return by adapting communication decisions to evolving mission conditions while explicitly accounting for operational risk. As such, this seed effort will help position DSU for sustained NASA-relevant research and future collaborations in resilient space communications, autonomy, and next-generation mission operations.

References

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2. Z. Zhang, X. Lin, G. Xue, and K. S. Chan, "AEGIS: Throughput-guaranteed resilient routing via a conditional value-at-risk approach," accepted to *IEEE/ACM Transactions on Networking*, 2026.
3. X. Lin, Z. Zhang, Z. Zhang, and G. Xue, "Task offloading across unreliable edge networks via distributional dynamic programming," accepted to *the IEEE INFOCOM 2026 Workshops (ISAC-FutureG)*, 2026.
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10. J. Wan, S. Lin, Z. Zhang, J. Zhang, and T. Zhang, "Scheduling Real-time Wireless Traffic: A Network-aided Offline Reinforcement Learning Approach," *IEEE Internet of Things Journal*.

2. Plan for Seeking External Funding.

This seed project will be used to position a larger external funding effort centered on intelligent, risk-aware scheduling for hybrid RF/optical space communication networks. The primary external target will be NASA programs aligned with space communications, autonomy, and resilient mission operations, including future NASA EPSCoR, STTR/technology transition opportunities, and related NASA research solicitations in space communications and onboard autonomy. In parallel, I will also explore complementary opportunities from NSF and DoD programs that support trustworthy AI, wireless networking, and resilient edge intelligence, especially where methods developed in this project can transfer to broader cyber-physical and mission-critical communication systems.

We currently have an active research connection with a NASA collaborator (*Dr. Mahmooda Sultana*) at Goddard Space Flight Center, whose expertise in space systems and mission-driven technology development provides an important pathway for aligning the proposed work with NASA needs. This seed project will strengthen that connection by producing preliminary technical results, simulation benchmarks, and a clearer problem formulation that can support future joint proposal development. I also plan to expand interactions with NASA-affiliated investigators and related contractors as the work matures, particularly those involved in space communications, autonomous operations, and optical networking technologies.

3. Relevance of Proposed Activities to NASA EPSCoR RID Mission and Relation to Existing Research.

The project is well aligned with the NASA EPSCoR RID mission because it contributes to Delaware's research infrastructure, science and technology capabilities, and higher education ecosystem. At DSU, the project will help establish new research capacity at the intersection of AI, networking, and space communications, while providing research training opportunities for undergraduate and graduate students in engineering and computer science. It will also create a foundation for sustained collaboration with NASA researchers and for broader engagement with NASA-related partners. These linkages will include technical interaction with a NASA Goddard collaborator, joint problem framing informed by NASA mission needs, and the development of simulation environments and algorithms that can support future collaborative proposals. More broadly, the project helps position Delaware to participate more actively in emerging aerospace and space-technology research directions with both scientific and workforce-development impact.

This work is also framed primarily in relation to the *Science Mission Directorate (SMD)*, which leads NASA's efforts in Earth Science, Heliophysics, Planetary Science, and Astrophysics and emphasizes scientific understanding of the Earth, the solar system, and the broader universe. In this context, the proposed research is relevant because future mission environments will increasingly rely on hybrid RF/optical links to support high-rate data delivery, but these links are inherently affected by changing channel conditions, intermittent connectivity, and operational uncertainty. By developing risk-aware and learning-enabled scheduling methods for such systems, this project addresses a fundamental challenge in mission communications: *how to make robust decisions that balance performance and reliability in dynamic environments.* In this way, the work directly supports NASA interests in resilient communications, onboard autonomy, and advanced space networking capabilities.

4. Budget Justification. (Total Budget: $20,564)

4.1. Key Personnel ($12,585)

The PI (Dr. Zhang) requests support for a one-month summer salary each year for this project. The PI will commit 100% of his time to the project during each summer period per year. The PI will oversee all aspects of the project including project management, evaluation, required purchases and (graduate and undergraduate) student hiring and mentoring. The 9-month salary of the PI is $85,000. Total salary from this project for the PI is $9,444. Total fringe from this project for the PI is $3,141. Fringe benefits are calculated at a 33.26% for full-time faculty staff and 9.16% rate for the part-time faculty staff.

4.2. Other Direct Costs ($1,500)

Publication Costs ($500). Publication costs will be incurred for reprographics materials, outreach, and journal publications of our research manuscripts.
Supply ($1,000). Supplies are requested to support the research, training, and project execution activities associated with the proposed work. These funds will be used to purchase occasional research-related supplies and small items needed for student training, laboratory activities, system prototyping, testing, data collection, and general project implementation. Such items may include small electronic components, cables, adapters, storage media, software-related accessories, and other expendable materials necessary for experimental setup and day-to-day research operations.

4.3. Indirect Costs ($6,479)

DSU's negotiated indirect cost rate (46%) is applied to all direct costs, except equipment and participant costs.

5. A vita for PI
5.1. Identifying Information

Name: Zhang, Zhaofeng

Persistent Identifier (PID) of the Senior/Key Person: https://orcid.org/0000-0002-4285-670X

Position Title: Assistant Professor

5.2. Organization and Location

Name: Delaware State University

Location: Dover, Delaware, United States

5.3. Professional Preparation

ORGANIZATION AND LOCATION	DEGREE	RECEIPT DATE	FIELD OF STUDY
Arizona State University, Tempe, Arizona, United States	Postdoctoral Fellow	01/2024 - 01/2026	Computer Science
Arizona State University, Tempe, Arizona, United States	PHD	01/2017 - 12/2023	Electrical Engineering
Arizona State University, Tempe, Arizona, United States	MS	08/2015 - 12/2016	Electrical Engineering
Huazhong University of Science and Technology, Wuhan, Hubei, China	BENG	09/2011 - 06/2015	Electrical Engineering

5.4. Appointments and Positions

2026 - present Assistant Professor, Delaware State University, Dover, Delaware, United States

5.5. Products Most Closely Related to the Proposed Project

1. J. Wan, S. Lin, Z. Zhang, J. Zhang, and T. Zhang, "Scheduling Real-time Wireless Traffic: A Network-aided Offline Reinforcement Learning Approach," *IEEE Internet of Things Journal*.
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3. Z. Zhang, X. Lin, G. Xue, Y. Zhang, and K. S. Chan, "Multi-Hop Relay-Aided Task Offloading for Tactical Edge Computing," in *Proc. IEEE Military Communications Conference (MILCOM)*, 2025, pp. 1572–1577.

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5. Z. Zhang, X. Lin, G. Xue, and K. S. Chan, “AEGIS: Throughput-guaranteed resilient routing via a conditional value-at-risk approach,” manuscript under revision for submission to *IEEE/ACM Transactions on Networking*, 2026.
6. X. Lin, Z. Zhang, Z. Zhang, and G. Xue, “Task offloading across unreliable edge networks via distributional dynamic programming,” in *Proceedings of the IEEE INFOCOM 2026 Workshops (ISAC-FutureG)*, 2026.

5.6. Other Significant Products

1. Zhaofeng Zhang, Sheng Yue, Junshan Zhang. Towards Resource-Efficient Edge AI: From Federated Learning to Semi-Supervised Model Personalization. IEEE Transactions on Mobile Computing. 2024.
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