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Modeling the Performance of Priority Queueing for Space Communication

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Agenda:

1. Introduction
2. The Space Communication Link
3. Modeling of Priority Queues
4. Results
5. Conclusion & Future Work

1. Introduction

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Introduction

- Increase in space missions and **increased communication demand** [1], [2]
- Prioritization proposed to meet **Quality of Service (QoS)** requirements [3]

⇒ Modelling is useful to predict the expected performance and verify results

Figure 1: Isar Aerospace Spectrum Rocket Launch Sept 2026 [4]

Introduction

- **Idea:** Applying queueing theory to model the end-to-end delay distribution of bundles with priorities

Figure 1: Isar Aerospace Spectrum Rocket Launch Sept 2026 [4]

2. The Space Communication Link

The Space Communication Link

- Considering a link between **Earth and Moon**
- Three states model the link's **temporal behavior**: [3], [5]
  - Success (S)
  - Short-Term Loss (ST)
  - Long-Term Loss (LT)
- Transition probabilities fitted to real-world observations

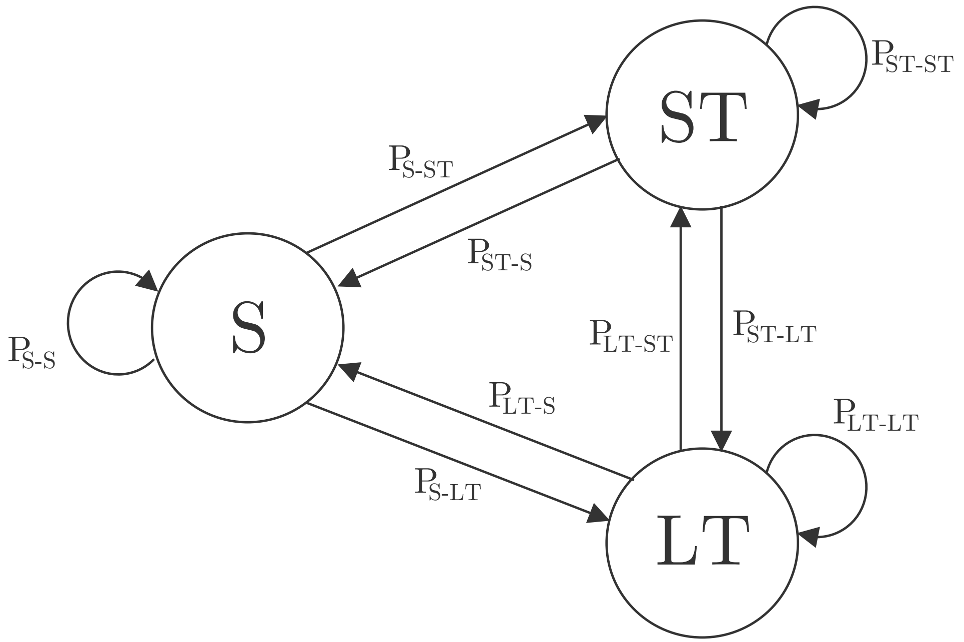

Figure 2: Markov Chain for the channel state

The Space Communication Link

- Stop-and-Wait ARQ gives the **service time**, including retransmissions
- Propagation dominates the round-trip time
- Exponential fit for the queueing model

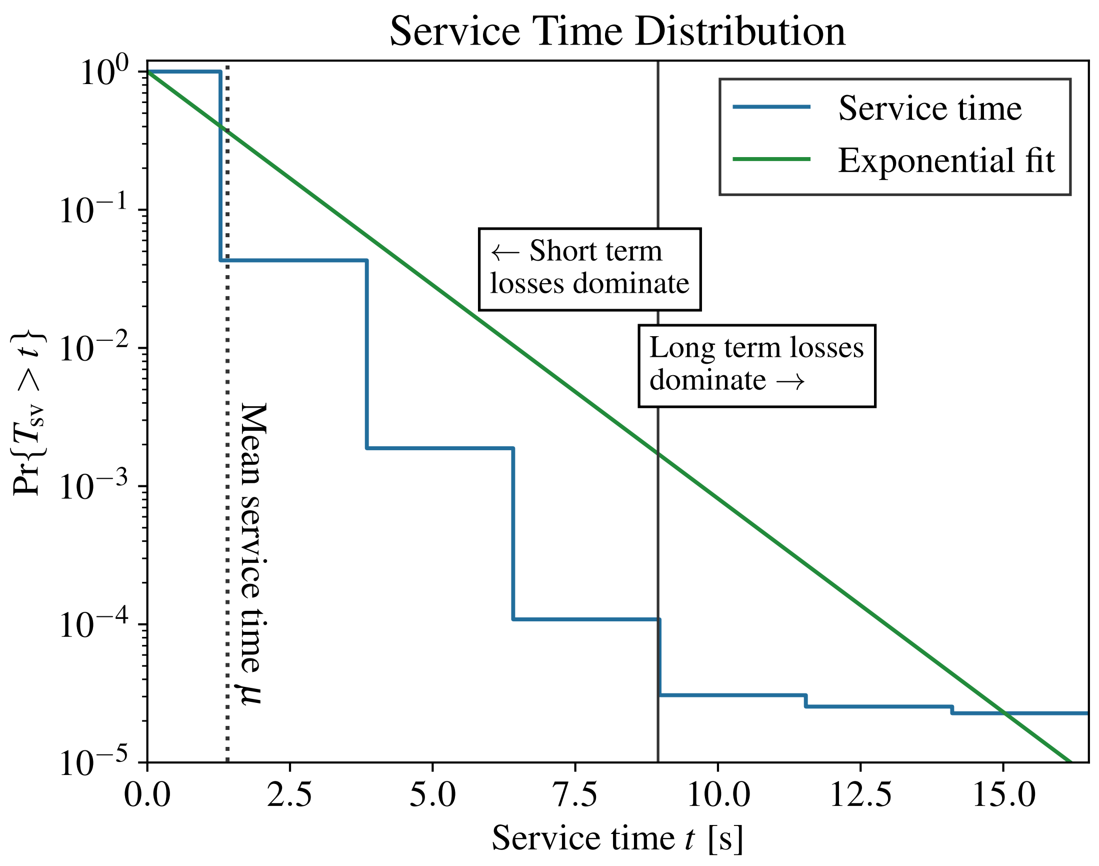

Figure 3: Service time distribution

3. Modeling of Priority Queues

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Scenario

- Deterministic bundle arrivals with rate λ aligned with [3]
- Split into two **non-preemtive** priority classes:
  - High priority with share q_h
  - Low priority with share q_ℓ
- Delay D_h decomposed into queueing and service

$$D_h = \underbrace{W_h}_{\text{queueing}} + \underbrace{S}_{\text{service}}$$

- Exponential service with rate μ from the link model for queueing
- Exact service time distribution for service also with rate μ
- **We only model the delay distribution of the high priority bundles**

Embedded Markov Chain

- Embedded Markov chain observed at arrival instances [6]
- State $(X \mid Y \mid Z)$
  - X, Y: # of high / low priority bundles in the system
  - $Z = 1$: High priority in service
  - $Z = 2$: Low priority in service

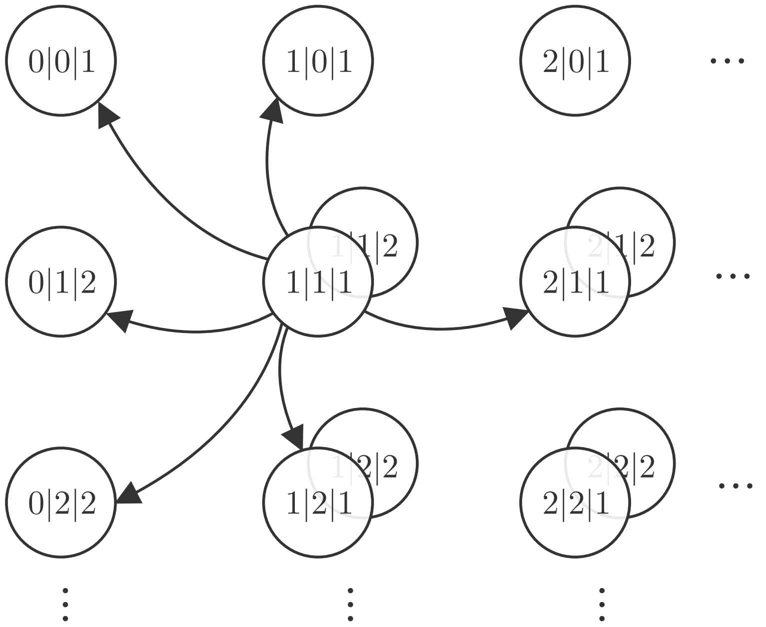

Figure 4: $(1 \mid 1 \mid 1)$: One of each class, high priority in service

State Transitions

- Between two arrivals, the service process may complete k bundles.
- Probability of k completions during one inter-arrival time:

$$a_k = \int_0^\infty \frac{(\mu t)^k}{k!} e^{-\mu t} f_A(t)\,\mathrm{d}t = \frac{(1/\rho)^k}{k!} e^{-1/\rho}, \qquad \rho = \frac{\lambda}{\mu}$$

No departure

$$(1\,|\,1\,|\,1) \xrightarrow{a_0 q_h} (2\,|\,1\,|\,1)$$

New high priority bundle joins the queue.

One departure

$$(1\,|\,1\,|\,2) \xrightarrow{a_1 q_\ell} (1\,|\,1\,|\,1)$$

Low priority service completes; high priority starts.

$\Rightarrow$ The same balance gives all transition probabilities.

Generating Functions

- Transition balance gives steady-state probabilities π_{ijk} [6]
- Generating functions collect these probabilities by service class:

$$\Pi(y, z) = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \pi_{ij1} y^i z^j \quad (Z = 1)$$

$$\Gamma(y, z) = \sum_{i=0}^{\infty} \sum_{j=1}^{\infty} \pi_{ij2} y^i z^j \quad (Z = 2)$$

- Allows to compute all possible steady state probabilities

Queueing Delay of a High Priority Bundle

- Three mutually exclusive cases at the arrival instant:

Case A_0:
- System is empty

Case A_i, $i \geq 1$:
- i high priority bundles
- High priority in service

Case B_i:
- i high priority bundles
- Low priority in service

- In A_i, the bundle waits for i services; in B_i, it also waits for the low priority service in progress.

Queueing Delay of a High Priority Bundle

- For exponential service, one service contributes $\mu/(\mu+s)$ in Laplace space.

$$\bar{w}_h(s) = \sum_{i=0}^{\infty}\left(\frac{\mu}{\mu+s}\right)^{i}\Pr\{A_i\} + \sum_{i=0}^{\infty}\left(\frac{\mu}{\mu+s}\right)^{i+1}\Pr\{B_i\}$$

- Using the generating functions:

$$\bar{w}_h(s) = \Pi\left(\frac{\mu}{\mu+s}, 1\right) + \frac{\mu}{\mu+s}\Gamma\left(\frac{\mu}{\mu+s}, 1\right)$$

High Priority Delay Distribution

- Closed-form waiting-time transform:[1]

$$\bar{w}_h(s) = \frac{(\mu + s)(1 - \eta) + \mu(\eta - \gamma)}{\mu + s - \gamma\mu}$$

- Adding the bundle's own exact service time:

$$\bar{d}_h(s) = \bar{w}_h(s)\,\bar{f}_S(s)$$

$\Rightarrow$ Inverse transform gives the end-to-end delay distribution

[1]Parameters η and γ obtained via fix-point expressions

4. Results

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Simulation Setup

- SimPy-based discrete event simulator
- Parameters varied:
  - Utilization ρ
  - High priority share q_h
- 40 runs per configuration
- Recording end-to-end delay of every bundle

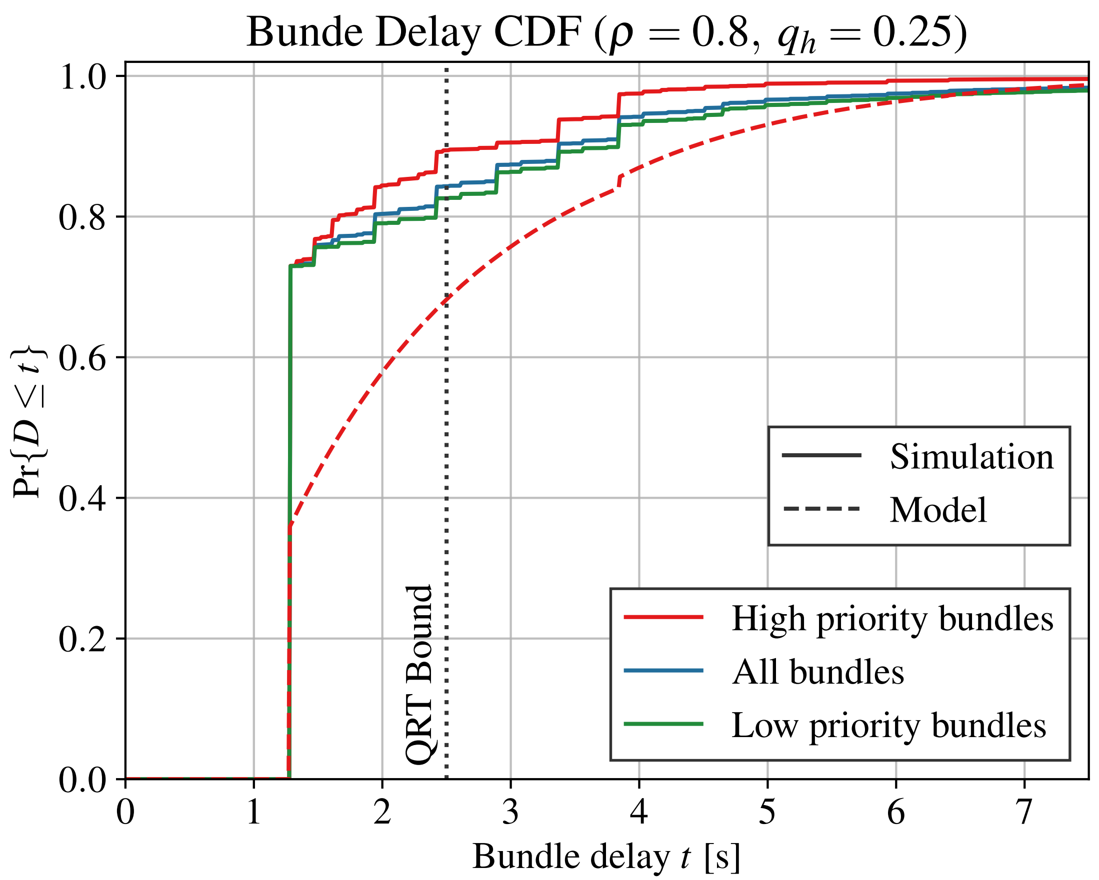

Figure 5: Delay CDF for $\rho = 0.8$, $q_h = 0.25$

End-to-End Delay Distribution

- Lower high priority delay, at the expense of low priority traffic
- Model captures:
  - Propagation minimum
  - High priority CDF shape
  - Small tail above 6 s
- Service approximation gives conservative delays

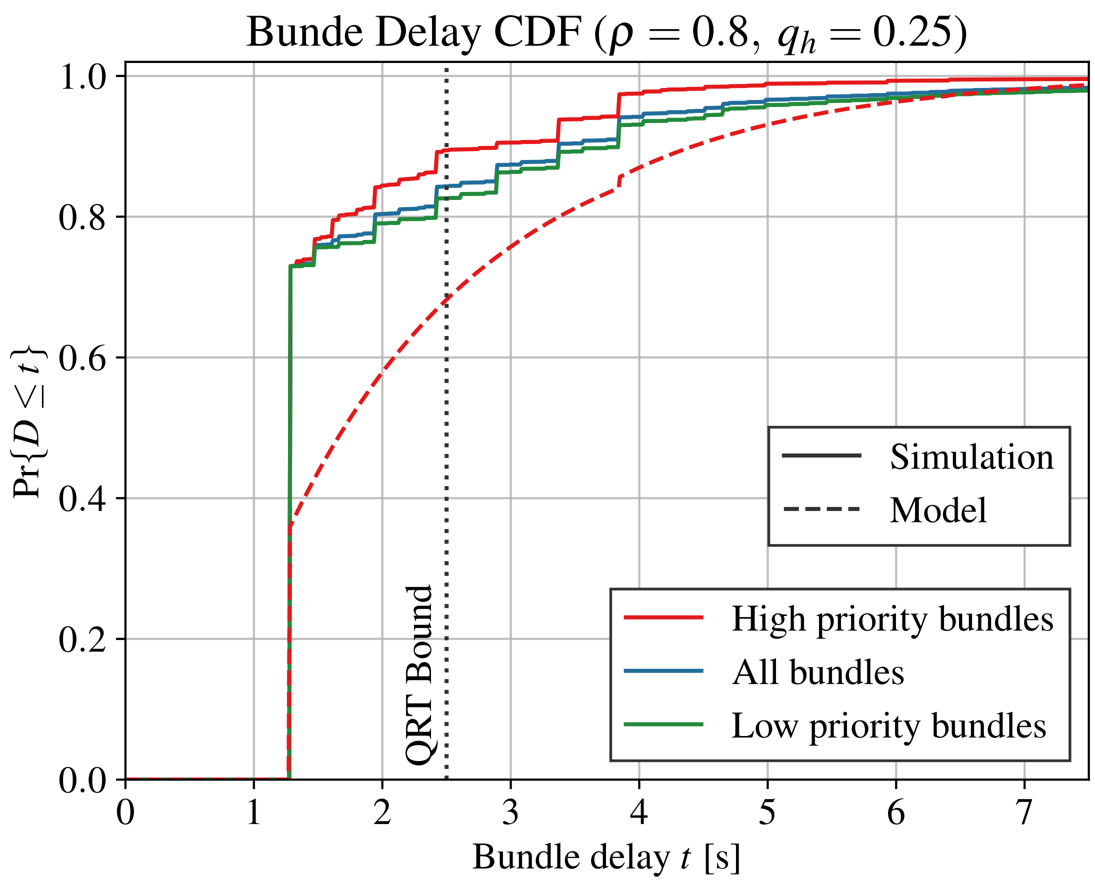

Figure 6: Simulation and model comparison

Quasi-Realtime Probability

- Quasi-Realtime probability: $\Pr\{D_h < 2.5\,\mathrm{s}\}$
- Negligible error at low utilization
- Error increases when queueing dominates
- **Up to** $38\,\%$ error at high ρ and q_h

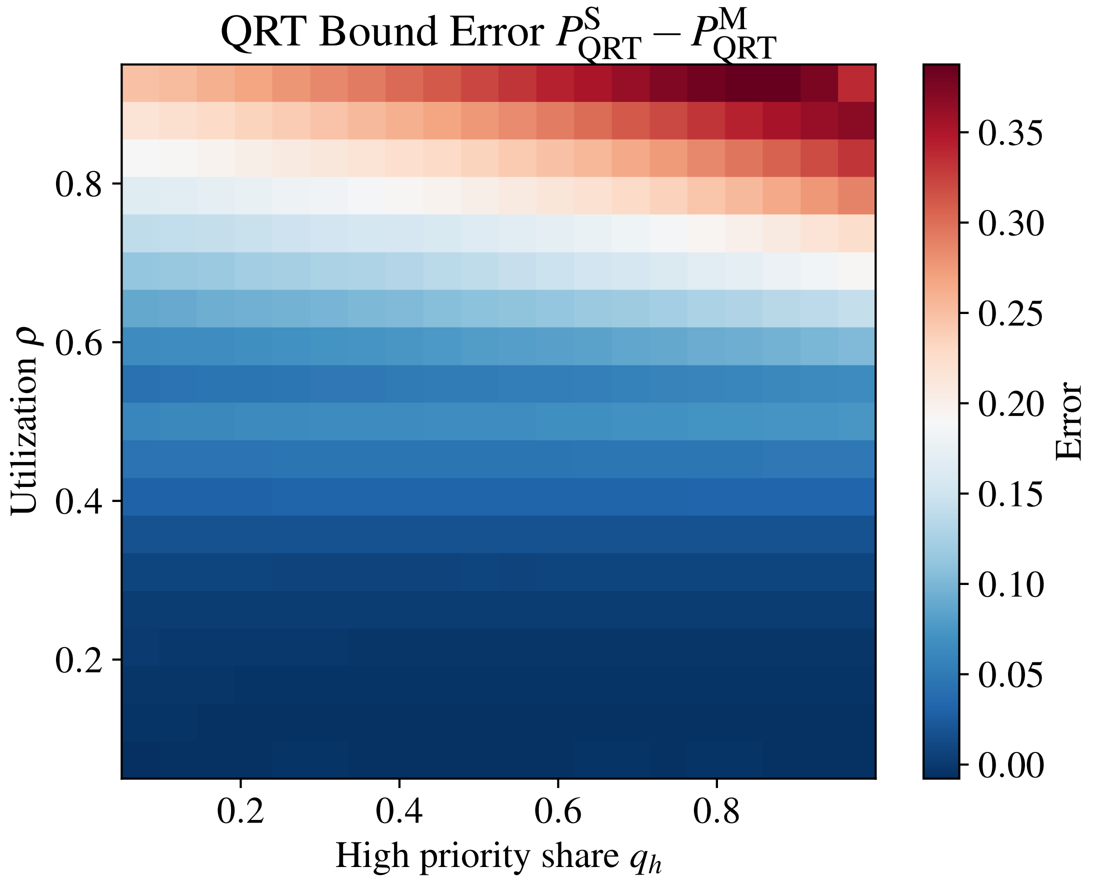

Figure 7: QRT probability error

Mean Bundle Delay

- Work-conserving priority: Overall mean delay unchanged
- Largest high priority gain at small q_h
- At $q_h = 0.1$: More than 40 % lower high priority delay
- Close model–simulation agreement

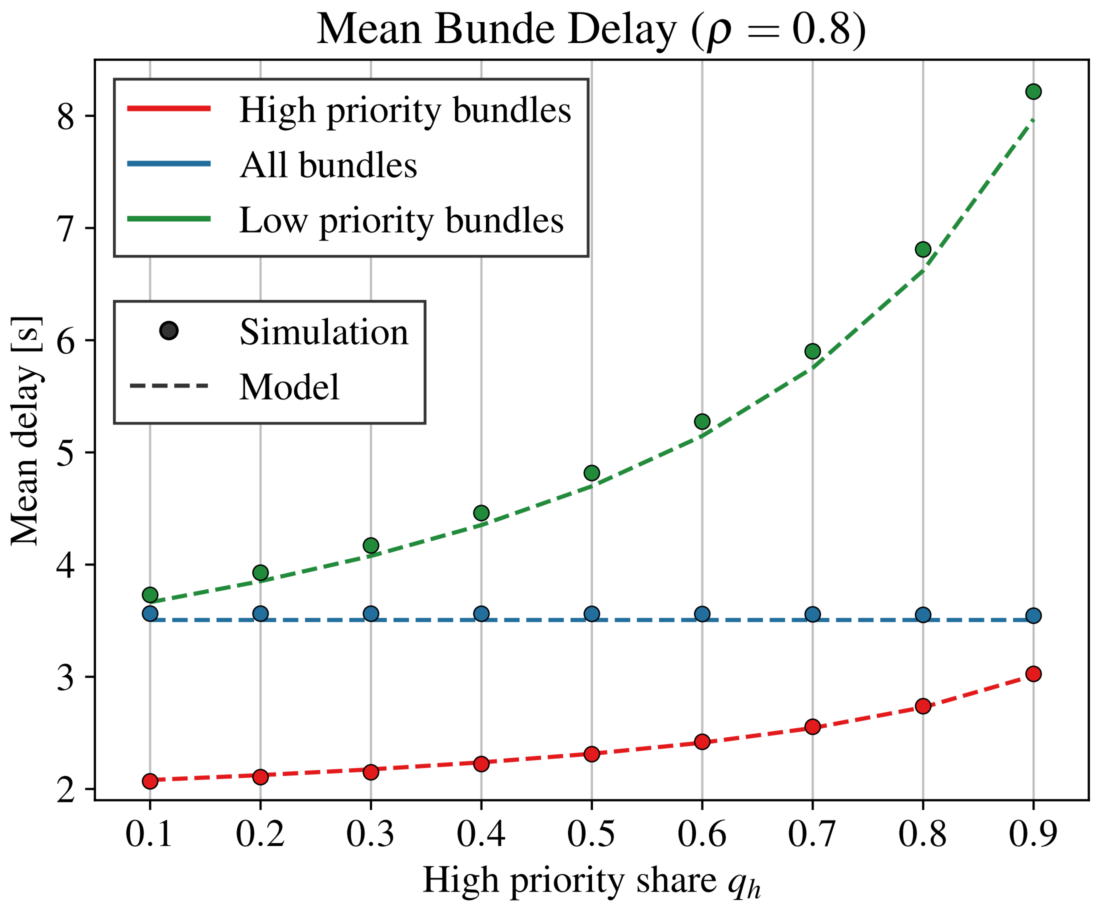

Figure 8: Mean delay over priority share

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Queue Dimensioning

- Dimension queues for the space communication link
- Generating functions give the high priority queue length distribution
- Mean queue lengths from Little's law:

$$L = L_h + L_\ell$$
$$\lambda \mathrm{E}[D] = q_h \lambda \mathrm{E}[D_h] + q_\ell \lambda \mathrm{E}[D_\ell]$$

$\Rightarrow$ Queue demand scales with delay and priority share

5. Conclusion & Future Work

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Conclusion & Future Work

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Conclusion:

- Derived a mathematical model for the **delay distribution** of high priority traffic
- Using a **D/M/1 queue** with retransmission-based service time
- **Accurate mean delay** for both priorities
- QRT estimate depends on utilization and prio share

Future Work:

- Delay over multi-hop paths with heterogeneous links
- Optimization of end-to-end paths

Thank You very much

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References

[1] M. Cosby et al., "The future lunar communications architecture," *Washington, DC USA: the Interagency Operations Advisory Group (Lunar Communications Architecture Working Group)*, 2022.

[2] Interagency Operations Advisory Group, "The Future Lunar Communications Architecture,", 2022. Accessed: Sep. 12, 2025. [Online]. Available: https://www.ioag.org/Public%20Documents/Lunar%20communications%20architecture%20study%20report%20FINAL%20v1.3.pdf.

[3] T. Algarra Ulierte, K. Kuladinithi, A. Timm-Giel, and F. Flentge, "Lunar communication services: Feasibility study on traffic prioritization of quasi-real time communications over dtns," in *2023 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, 2023, pp. 35–40. doi: 10.1109/WiSEE58383.2023.10289636.

[4] European Space Agency, "Isar aerospace achieves first launch to orbit from continental europe," Accessed: Sep. 14, 2026. [Online]. Available: https://www.esa.int/Enabling_Support/Space_Transportation/Boost/Isar_Aerospace_achieves_first_launch_to_orbit_from_continental_Europe.

[5] T. Algarra Ulierte, F. Flentge, J. Quintanilla, and A. Timm-Giel, "Characterizing space communication channel behaviour: An analytical approach with esa mission data validation," in *10th International Workshop on Tracking, Telemetry and Command Systems for Space Applications (TTC)*, IEEE, 2025.

[6] R. Reed, "Priority queues," Ph.D. dissertation, Durham University, 1971.

[7] I. C. Internet Society, *Solar system internet: Architecture and governance*, 2024. Accessed: Sep. 12, 2025. [Online]. Available: https://drive.google.com/file/d/1anMcVEqXjNtk5gdo_qce28SowusXKkfi/view.

[8] K. Scott and S. Burleigh, "Bundle protocol specification," Tech. Rep., 2007.

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