DSNS: The Deep Space Network Simulator

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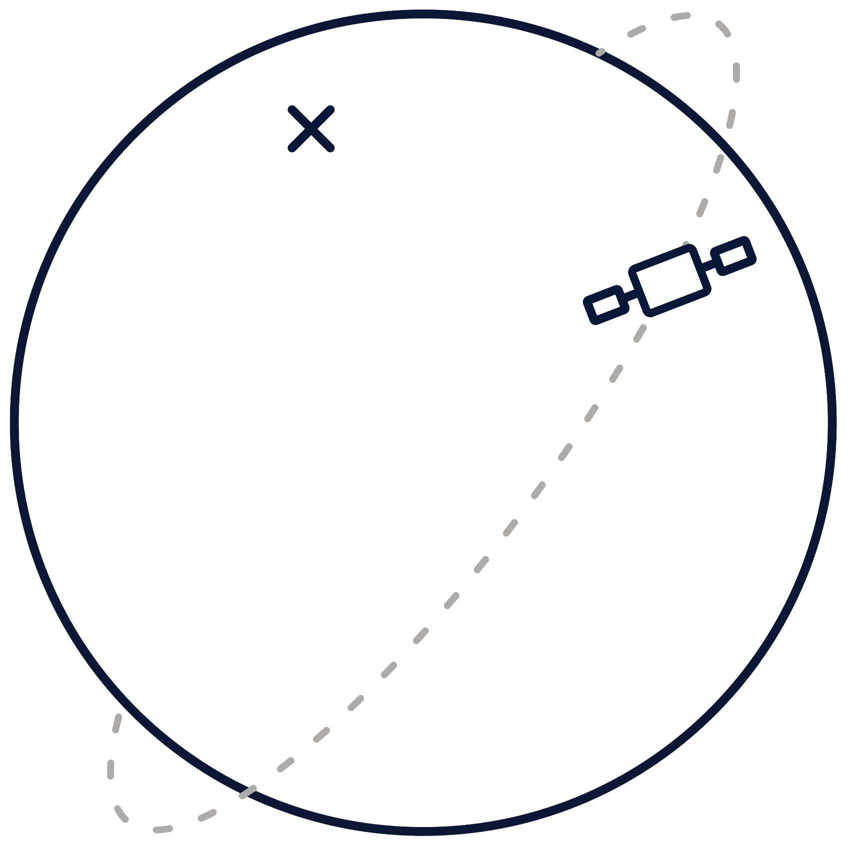
Overview

- For effective R&D and security analysis, we need to understand space at the network level



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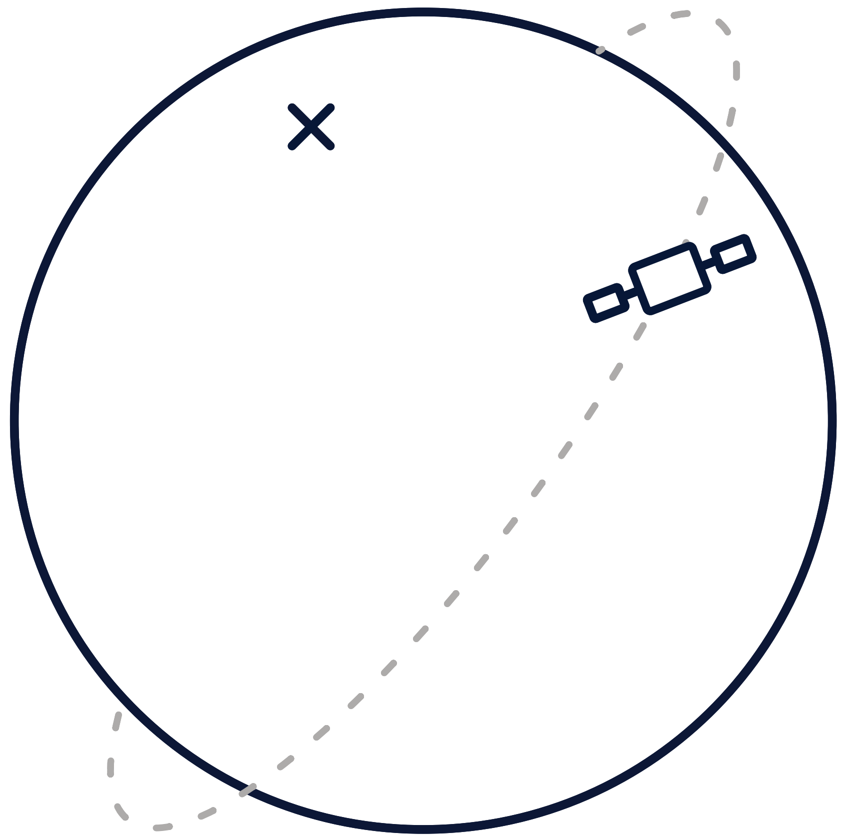
- Existing simulation tooling insufficient – lack of support for modern/emerging network characteristics



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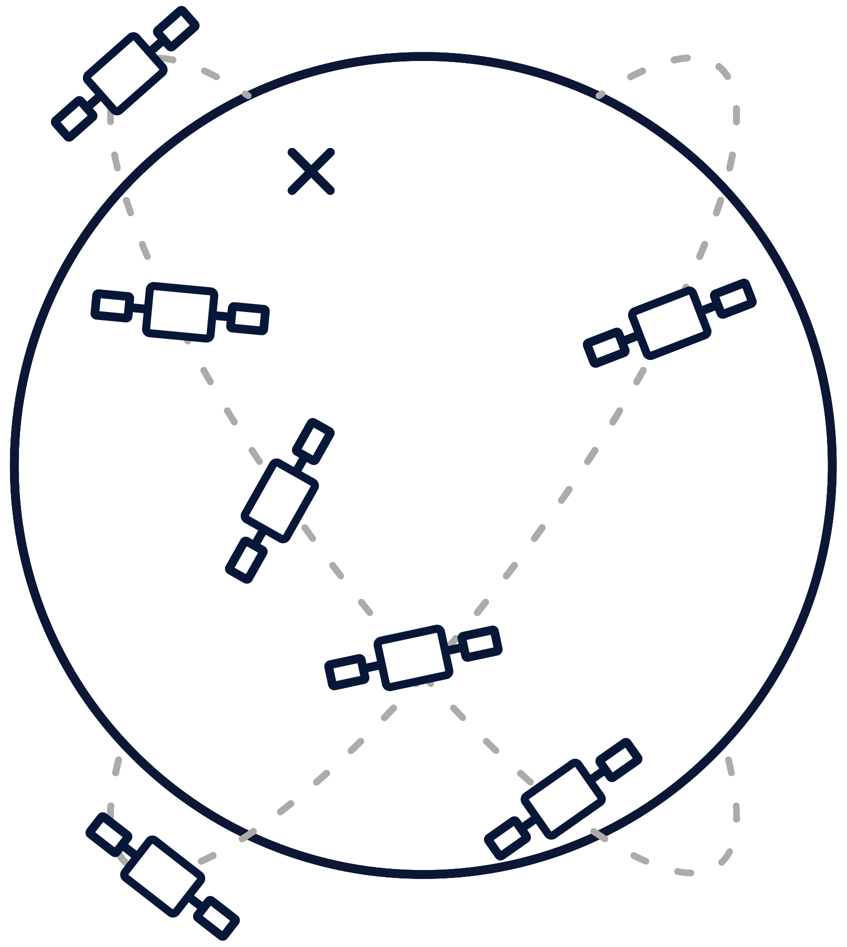
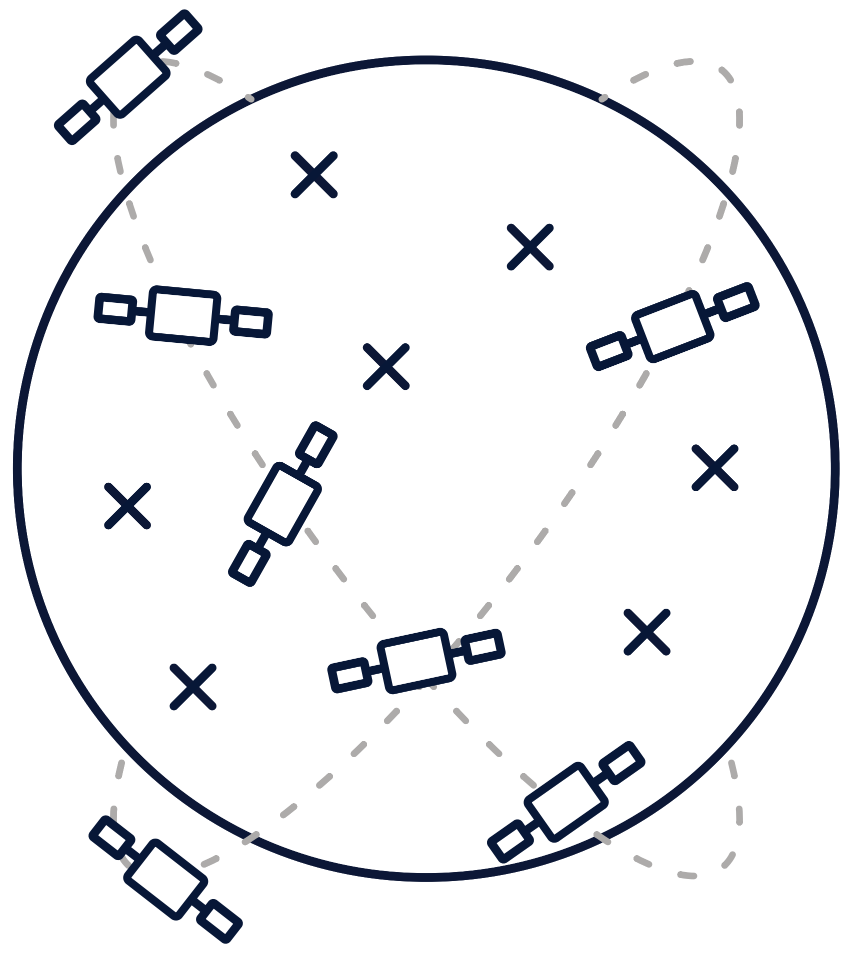


OVERVIEW

- For effective R&D and security analysis, we need to understand space at the network level
- Existing simulation tooling insufficient – lack of support for modern/emerging network characteristics
  - Megaconstellations
  - Ground Stations as a Service



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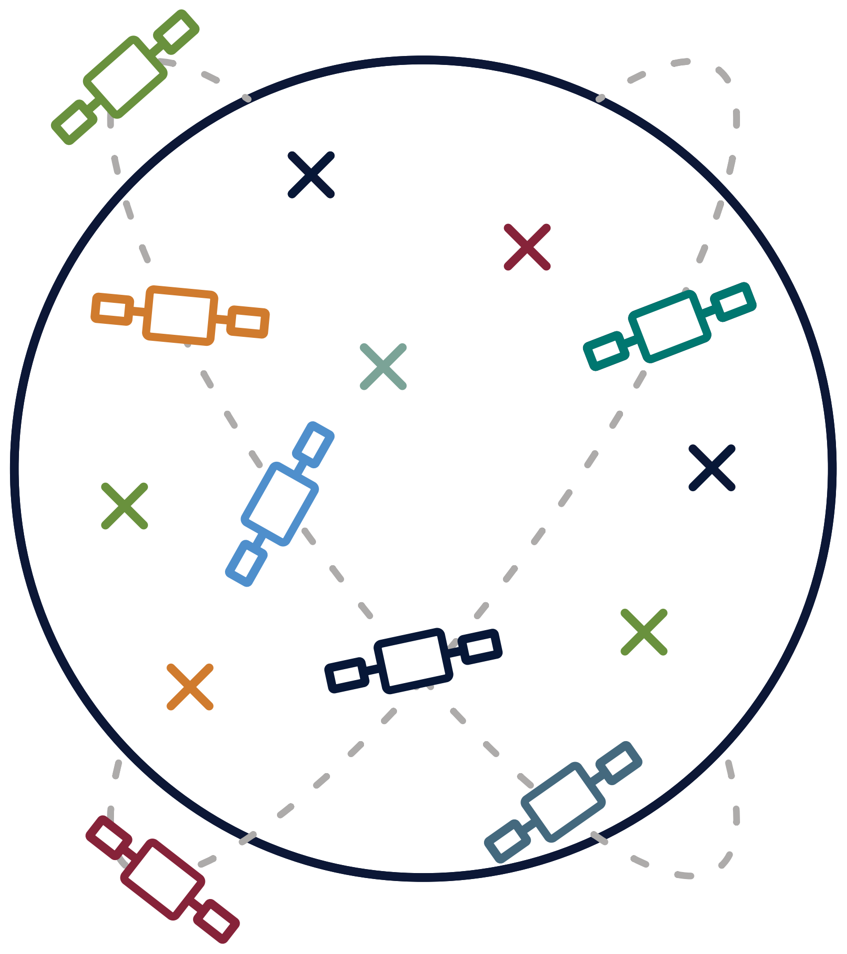

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  - Megaconstellations
  - Ground Stations as a Service
  - Federated Satellite Systems

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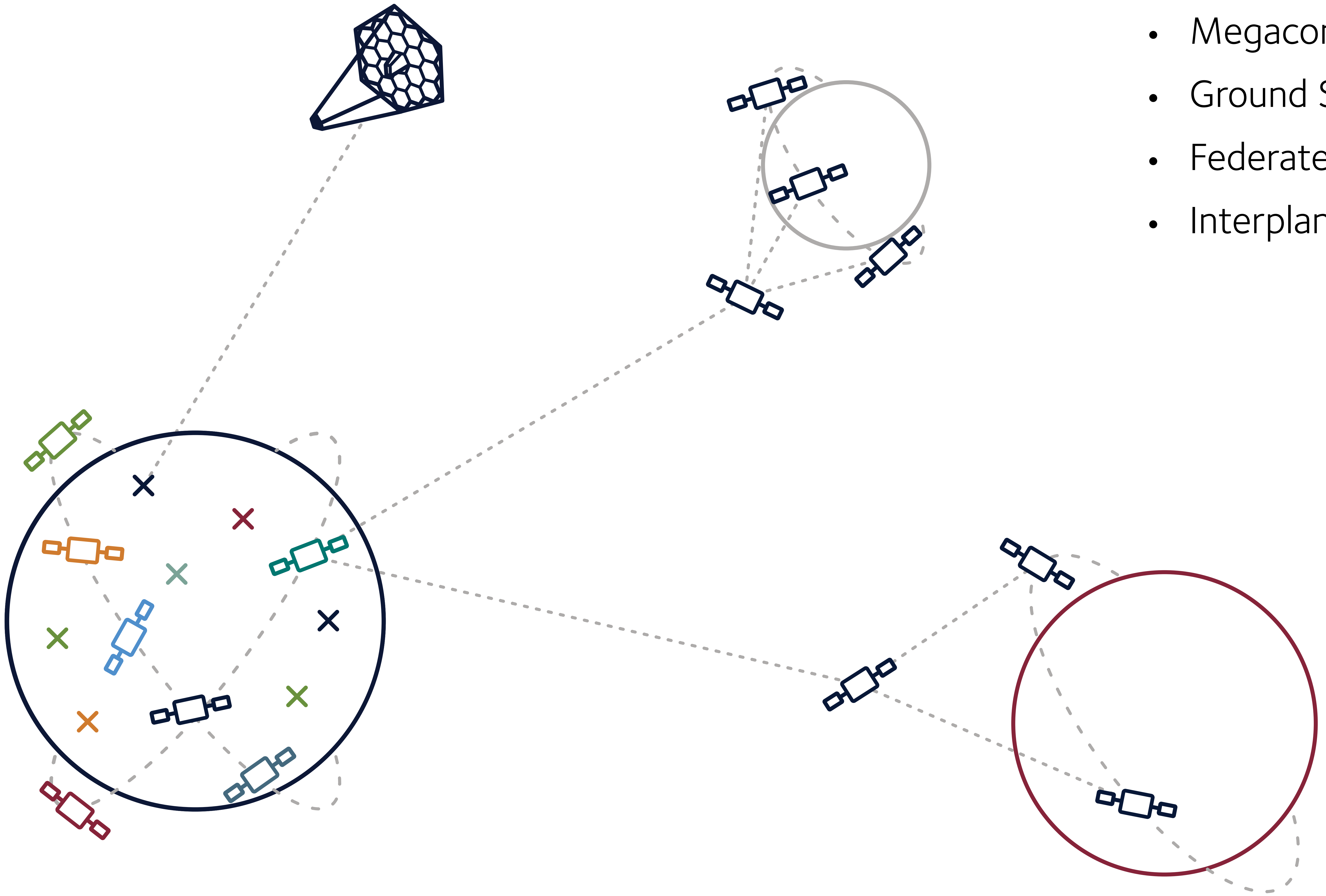

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  - Interplanetary Networks

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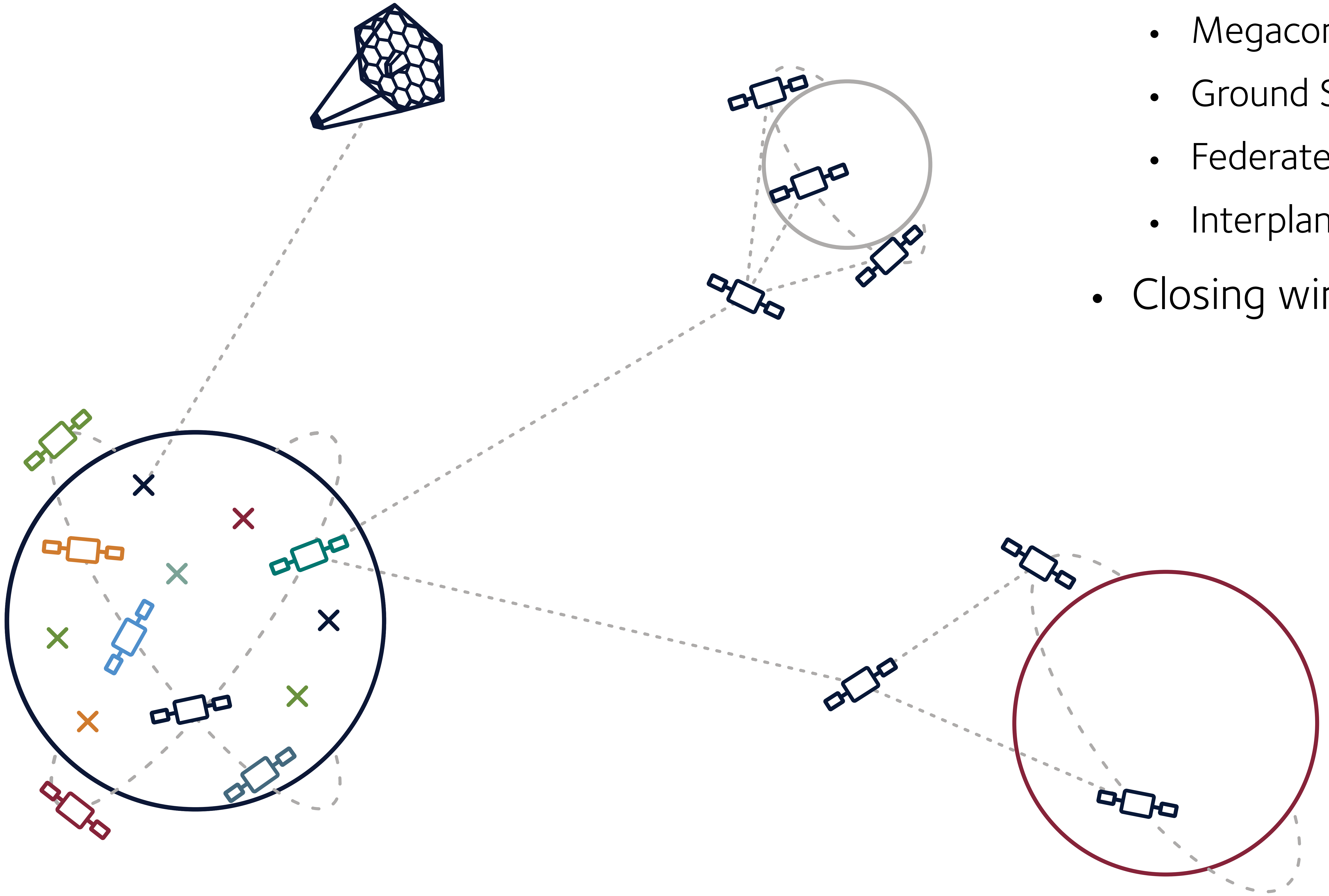

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- Closing window for secure-by-design

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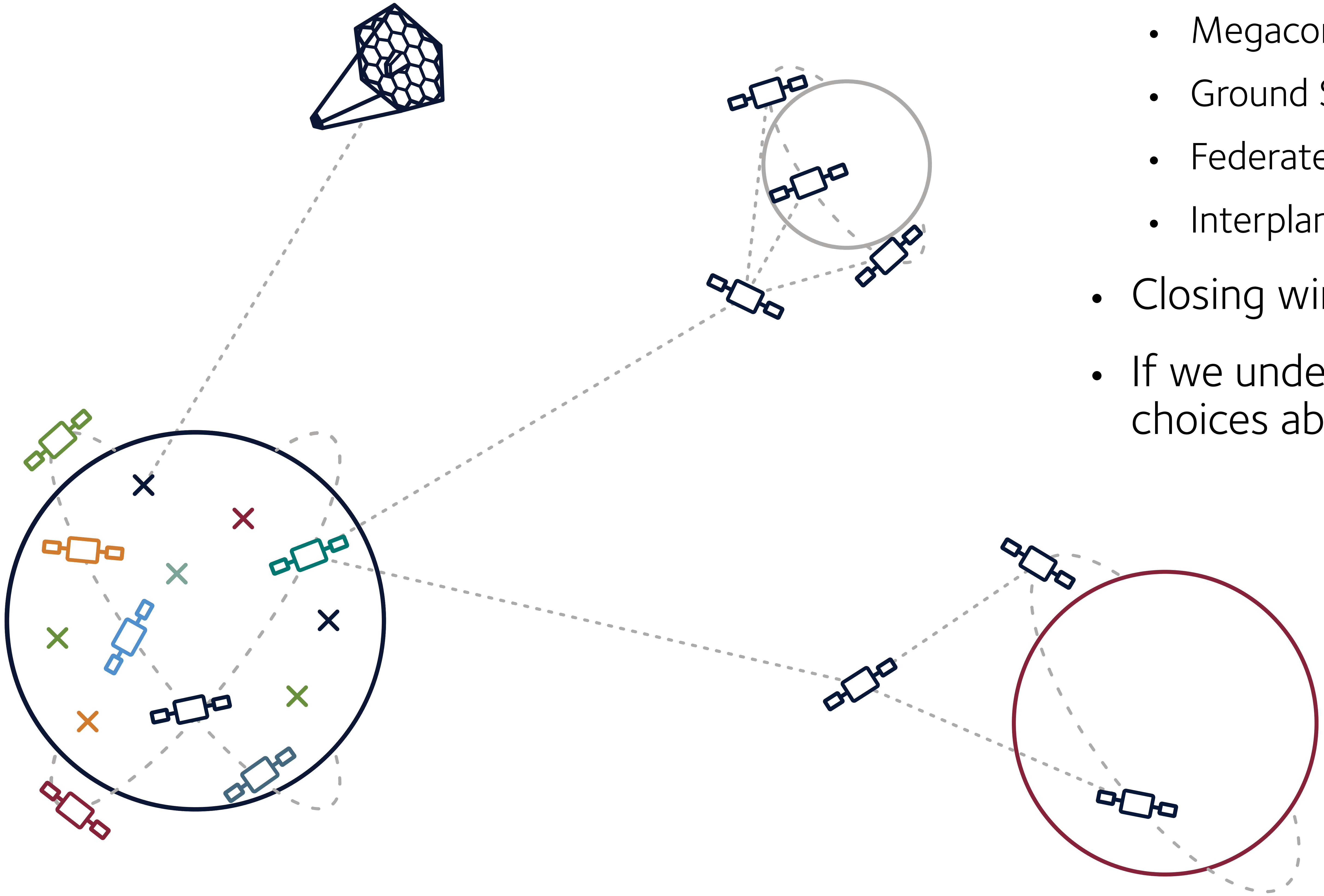

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    - Ground Stations as a Service
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    - Interplanetary Networks
- Closing window for secure-by-design
- If we understand the network, we can make informed choices about protocol design and governance

Simulation Tools

Existing Offerings

Name	Created by	Language	License	Released	Maintained	Summary
ONE Simulator [7]	TKK	Java	GPLv3	2007	✗	Lightweight DTN network simulator. Focused on small numbers of nodes with random movement.
NOS3 [8]	NASA	C	NOSA	2019	✓	Small satellite operational simulator. Simulates flight and ground software for single missions with high fidelity.
SpaceSecLab/ NSE2 [9]	ESA	—	Unreleased	—	—	Containerized satellite simulator with integrated network simulation. Realistic and configurable, possible integration with real hardware.
Hypatia [10]	ETH Zürich	C++/Python	GPLv2/MIT	2020	✗	Extension to ns-3, provides LEO constellation mobility for fixed ISLs. Now part of "SNS3" [11].
Celestial [12]	TU Berlin	Python	GPLv3	2022	✓	LEO system testbed based on micro-VMs, supporting software emulation for LEO networks.
StarryNet [13]	Tsinghua	Python	MIT	2023	✓	Simulator for integrated space and terrestrial networks, combining orbital simulation with Docker and network emulation.
$x$eoverse [14]	Surrey	Python	Non-commercial	2025	✓	LEO megaconstellation simulator based on Mininet [15]. Real-time simulation of large networks including dynamic ISLs.
Stardust [16]	TU Wien	C#	Apache 2.0	2025	✓	Scalable 3D network routing simulator, plugins to extend functionality. Fast, supports many nodes.
SatScope [17]	NUDT China	Python	Non-commercial	2025	—	LEO constellation network simulator based on VTK with a focus on satellite internet routing/coverage.

- A number of simulation tools already exist, satisfying a wide range of needs

Simulation Tools

Existing Offerings

Simulator	Orbital Simulation (**R1**)	Interplanetary (**R2**)	Dynamic connectivity (**R3**)	Dynamic Timesteps (**R4**)	Extensible (**R5**)	Scalable (**R6**)	Abstracted network stack (**R7**)
ONE Simulator [7]	○	○	●	●	●	◐	●
NOS3 [8]	○	○	◐	○	◐	○	○
SpaceSecLab/NSE2 [9]	◐	◐	◐	●	●	◐	○
Hypatia [10]	●	○	○	●	●	◐	◐
Celestial [12]	●	○	●	○	◐	◐	○
StarryNet [13]	●	○	●	○	◐	◐	◐
$x$eoverse [14]	●	○	◐	○	◐	◐	○
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Hypatia [10]	●	○	○	●	●	◐	◐
Celestial [12]	●	○	●	○	◐	◐	○
StarryNet [13]	●	○	●	○	◐	◐	◐
$x$eoverse [14]	●	○	◐	○	◐	◐	○
Stardust [16]	●	○	●	○	●	●	◐
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- Varying levels of feature support
- Space for something new?

DSNS

Deep Space Network Simulator

Built to address the gap in existing tooling:

DSNS

github.com/ssloxford/DSNS

DSNS

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Built to address the gap in existing tooling:

- Arbitrary satellite movement and connections

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Built to address the gap in existing tooling:

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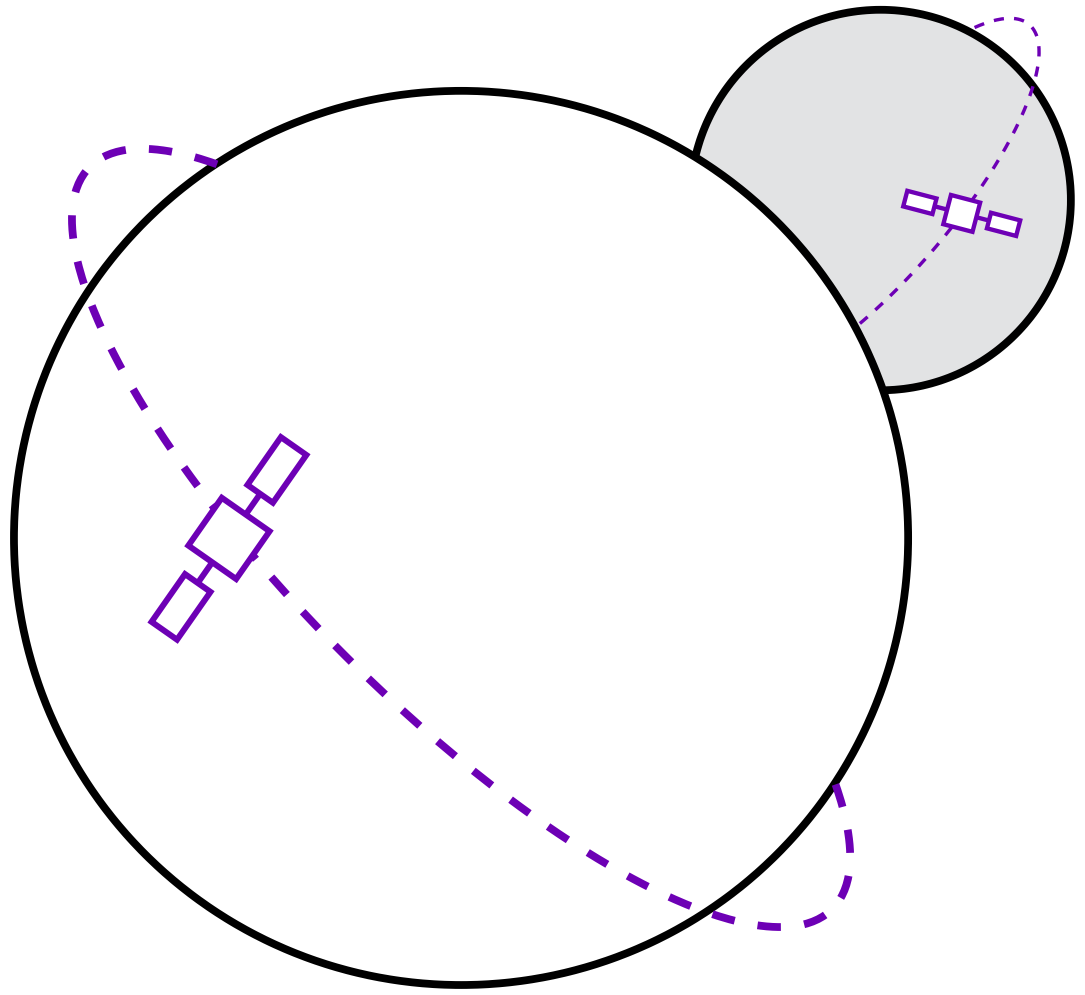
- Scalable to thousands of nodes



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Built to address the gap in existing tooling:

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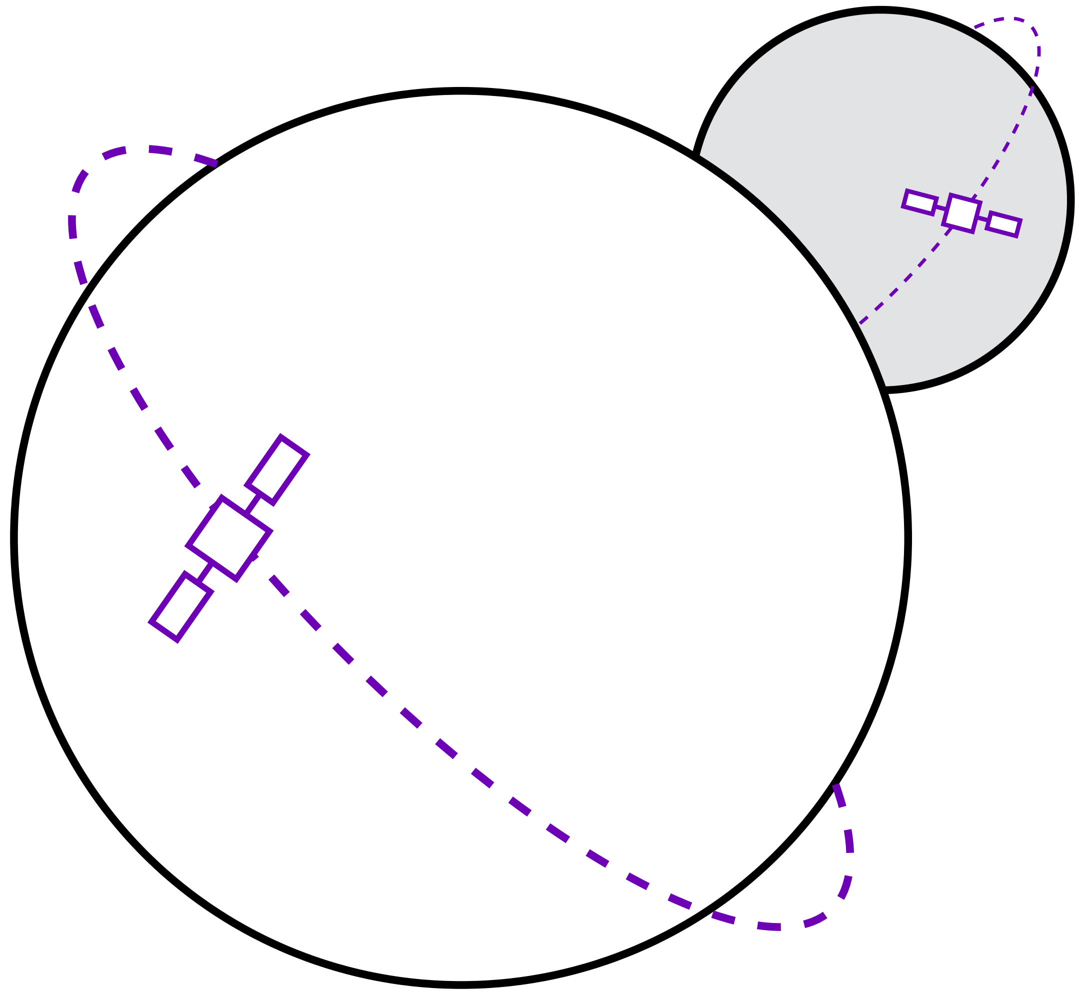
- Scalable to thousands of nodes
- Sub-millisecond precision, fast-forwarding through long gaps



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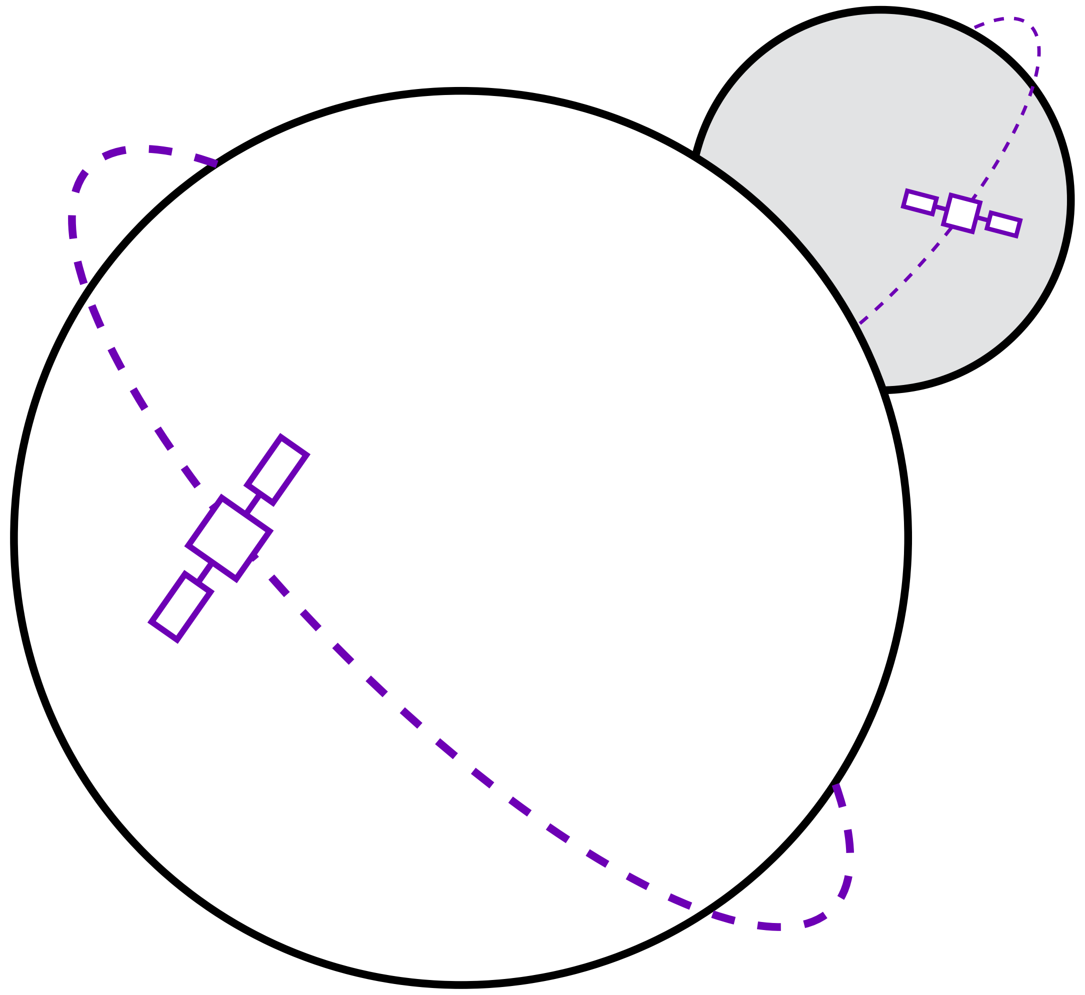

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- Arbitrary satellite movement and connections
- Scalable to thousands of nodes
- Sub-millisecond precision, fast-forwarding through long gaps
- Easily extensible via a simple Python interface
- Supports varying levels of abstraction
- Free and open source (GPLv3)

DSNS

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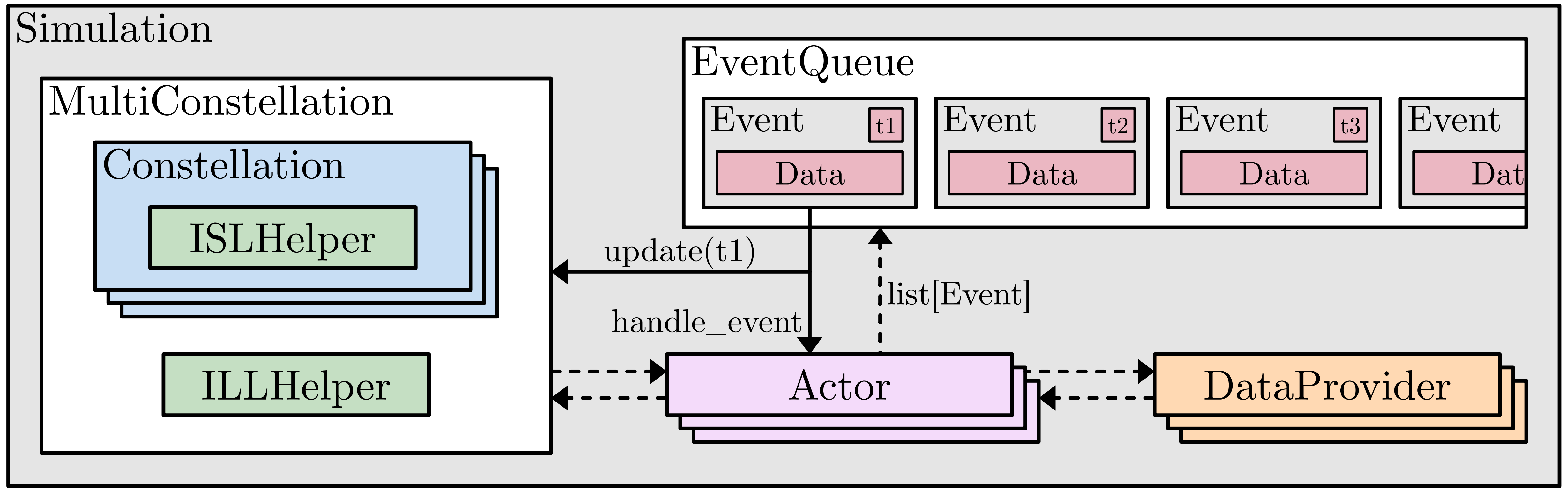
Architecture



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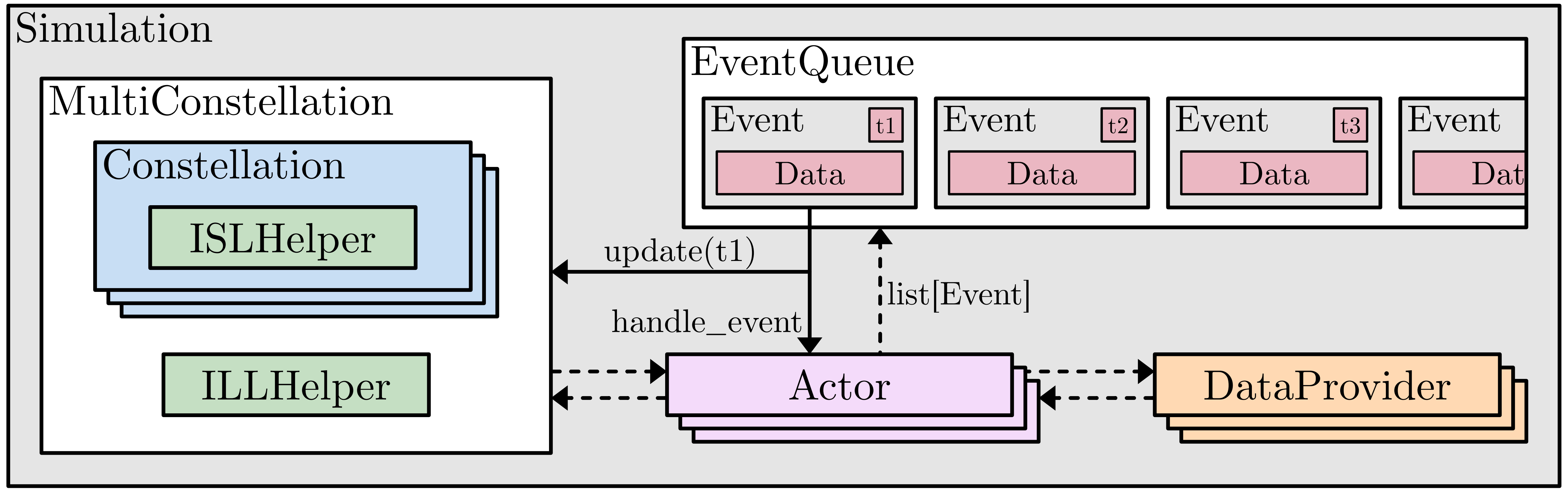

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- Simple event-based architecture enables complex functionality to emerge from simple building blocks

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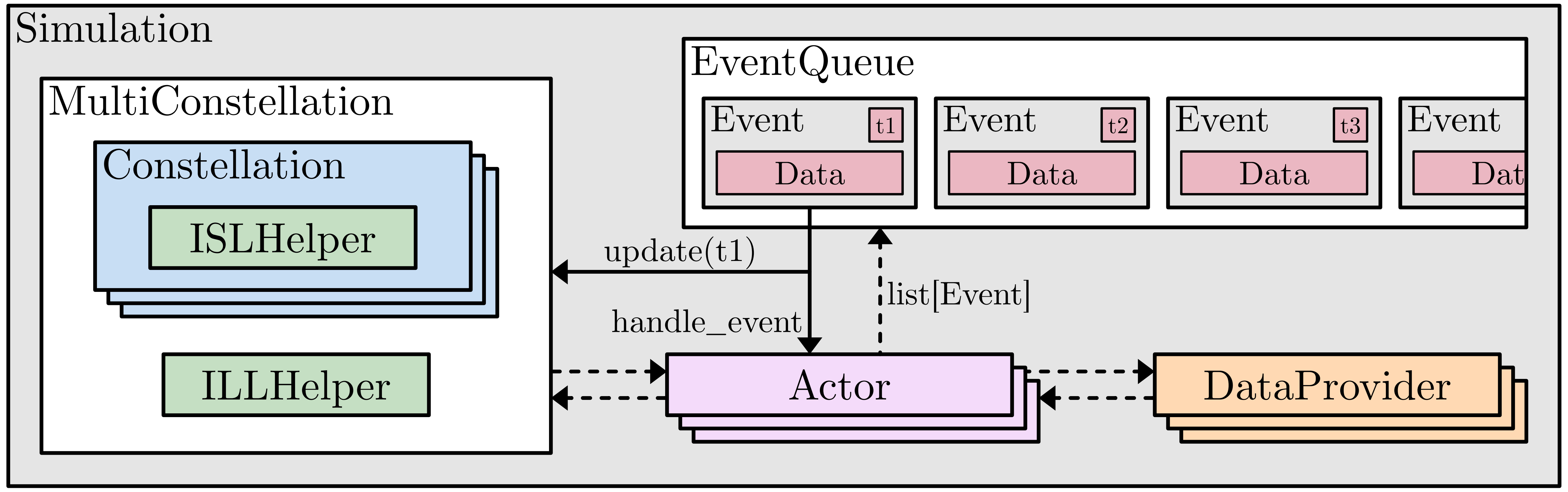

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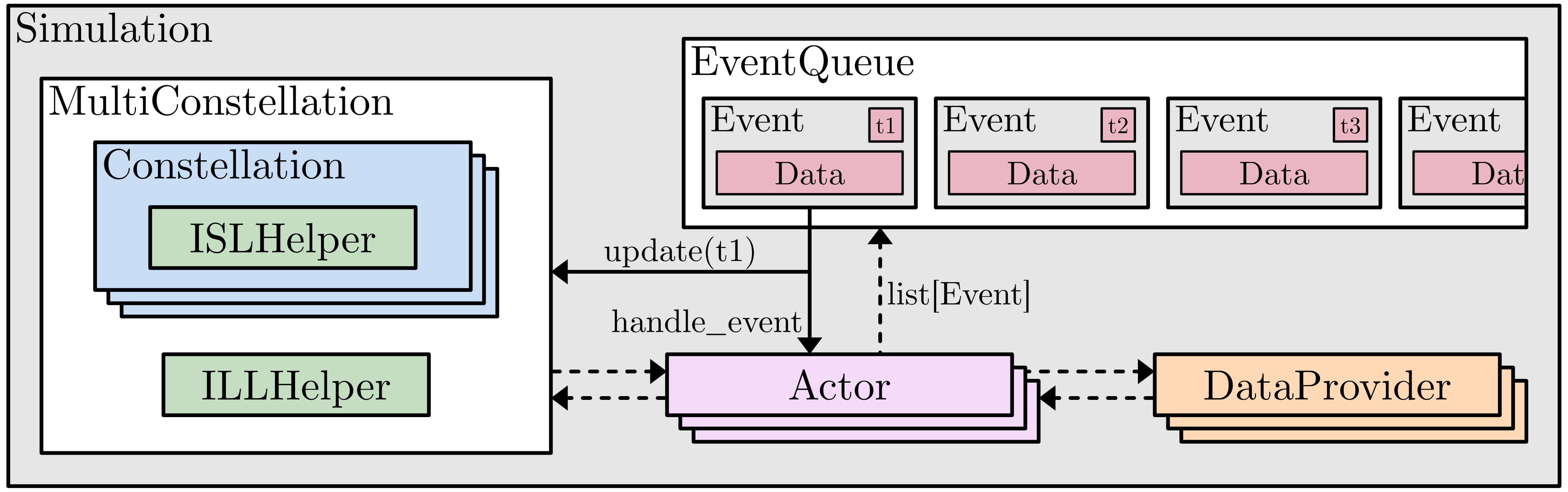

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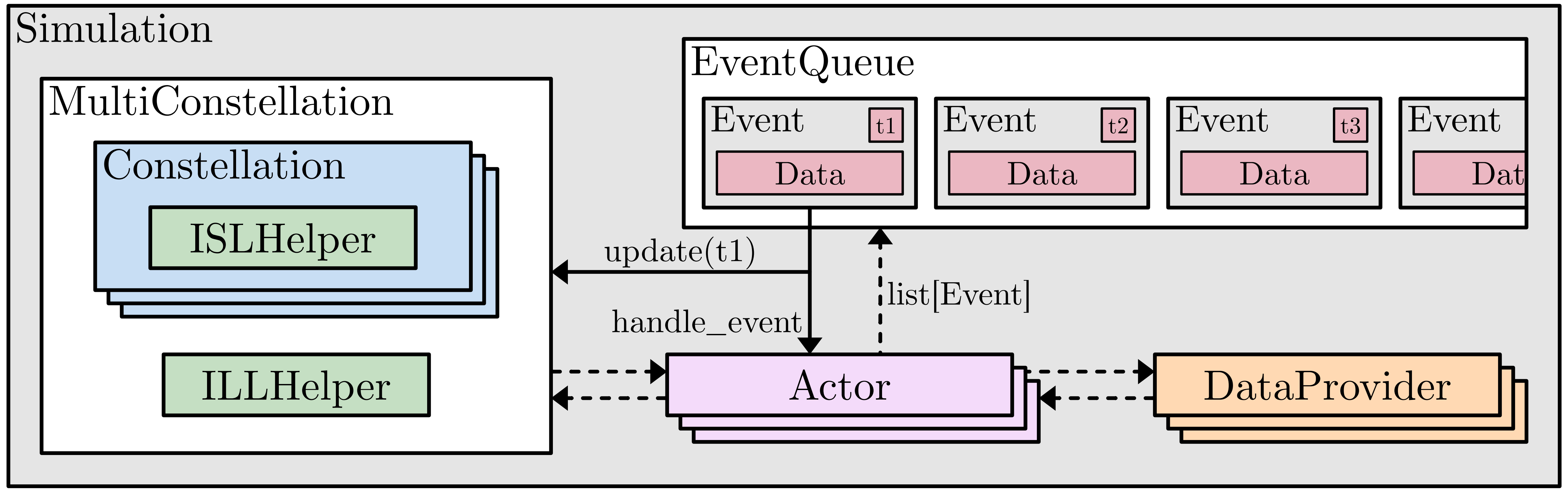
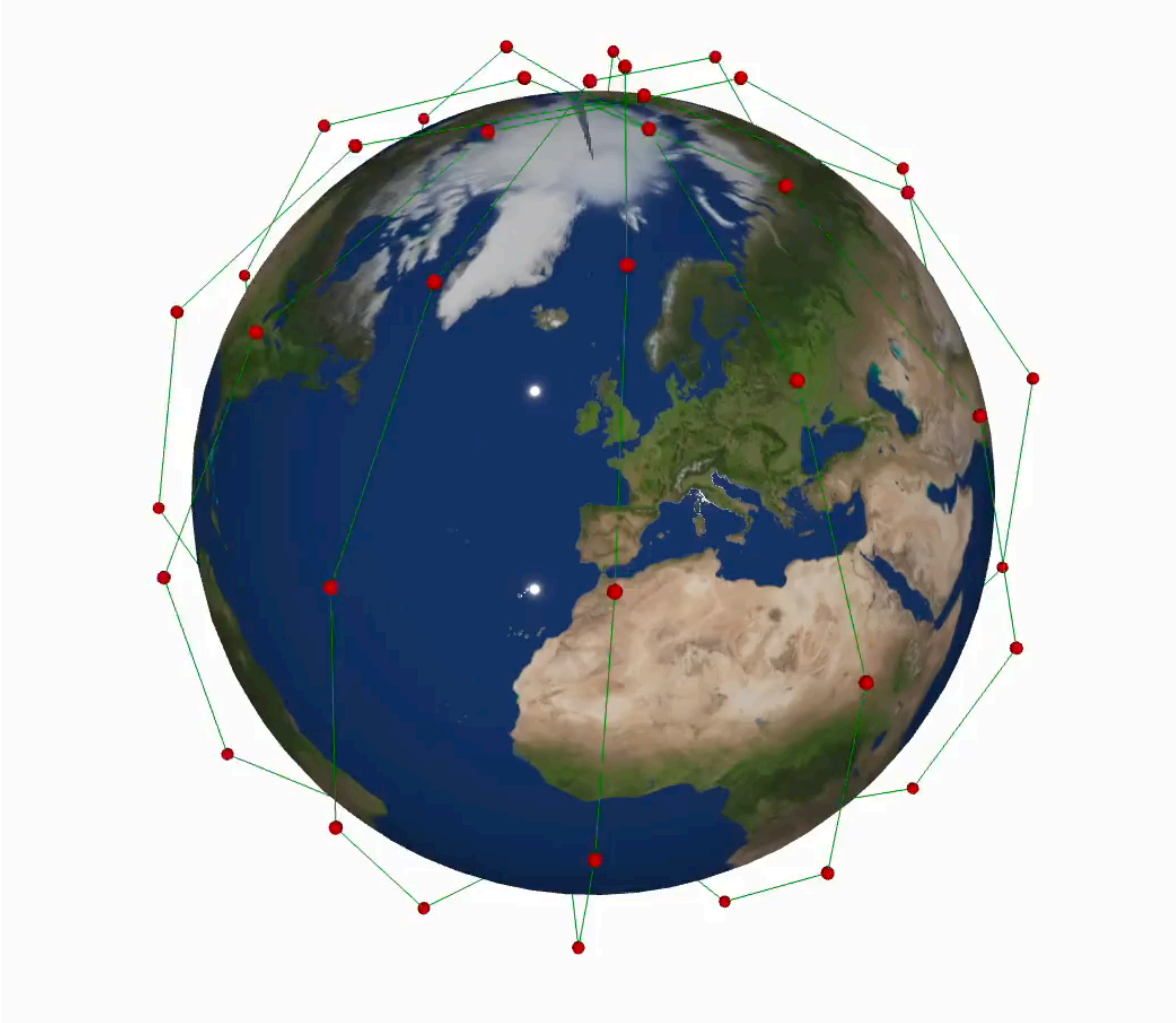
- Simple event-based architecture enables complex functionality to emerge from simple building blocks
- Additional functionality added in-place by simply including additional actors
- Build one layer at a time; forget about everything else

Mobility

Constellations defined by positions, TLEs, Walker definitions, or arbitrary functions





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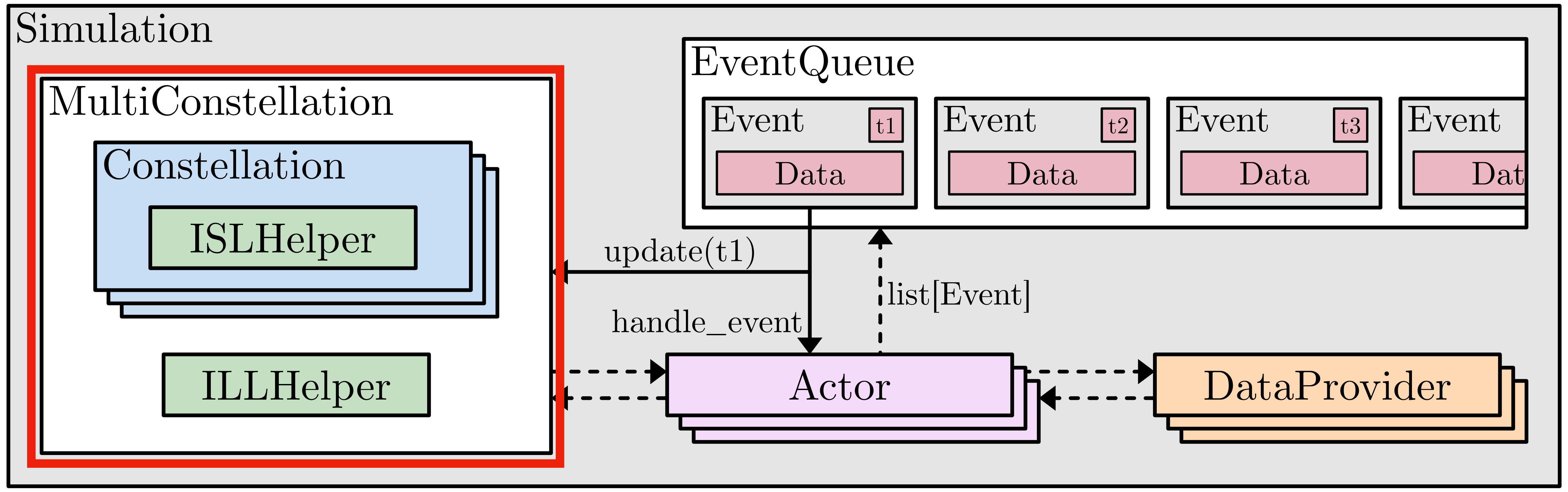

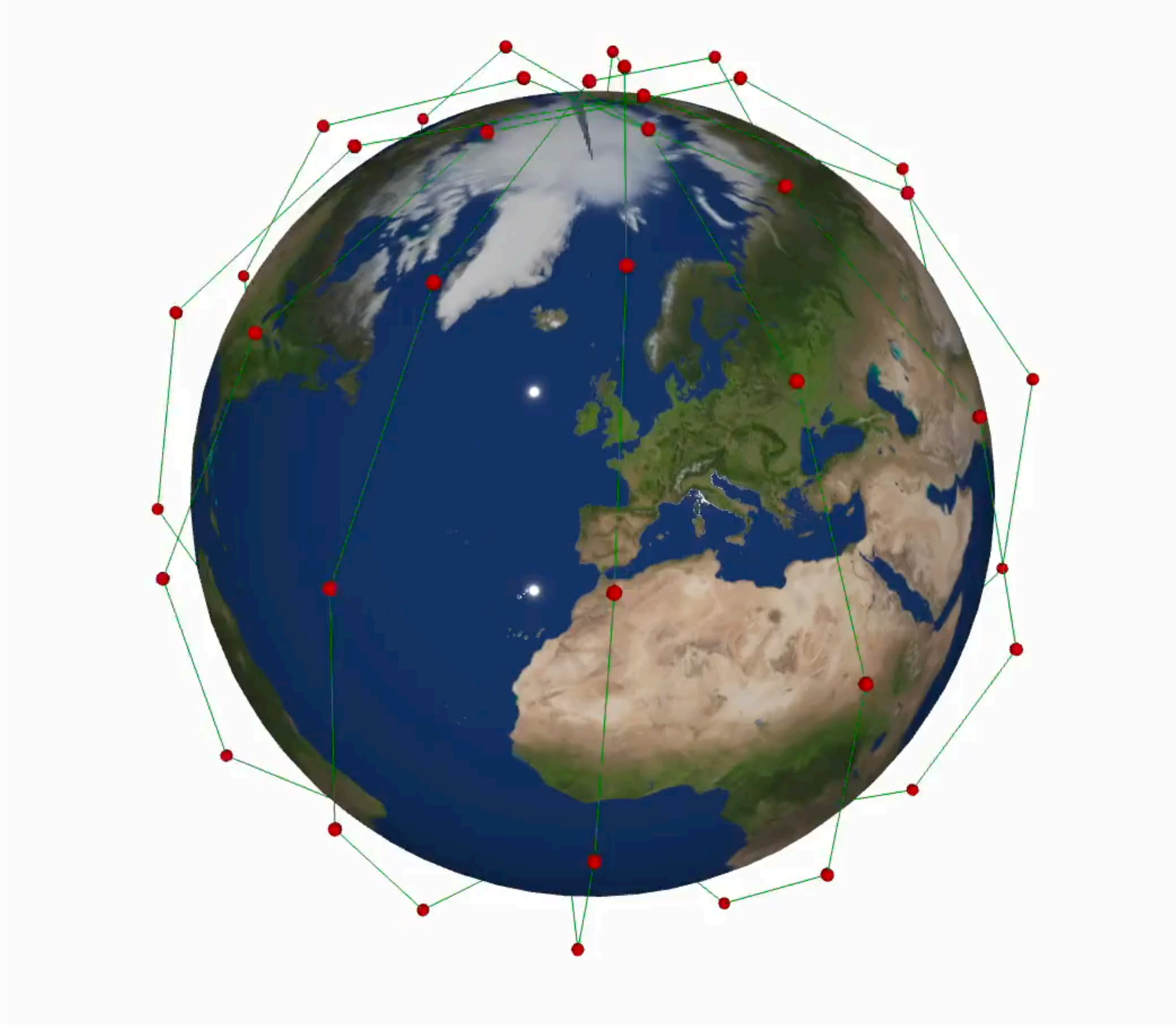

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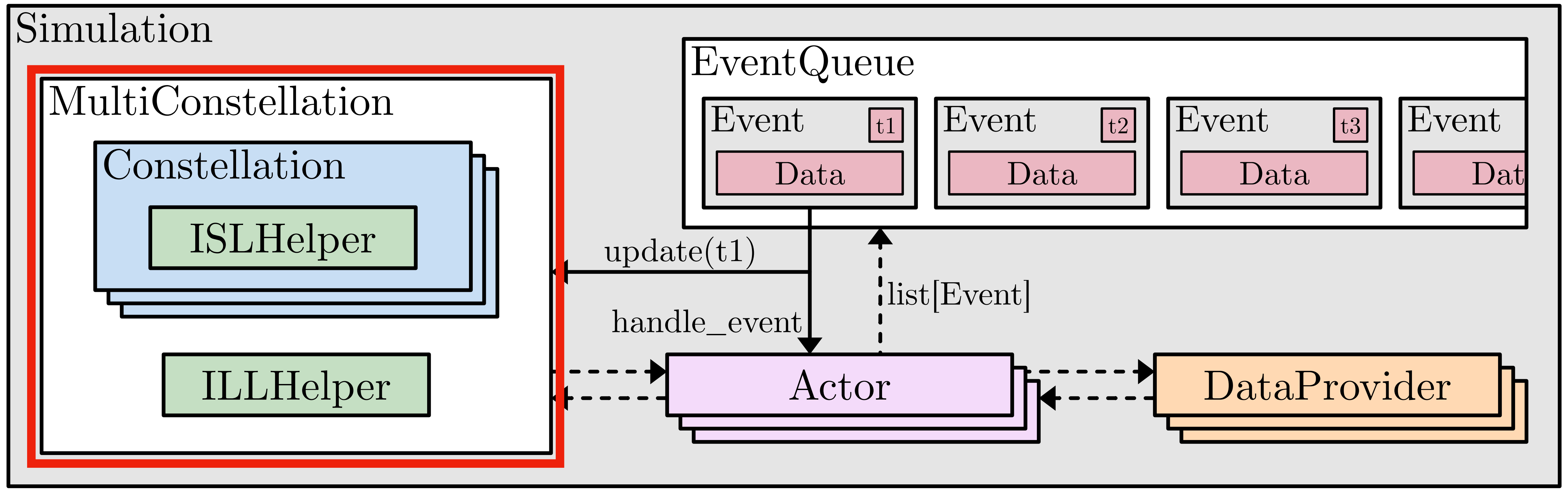

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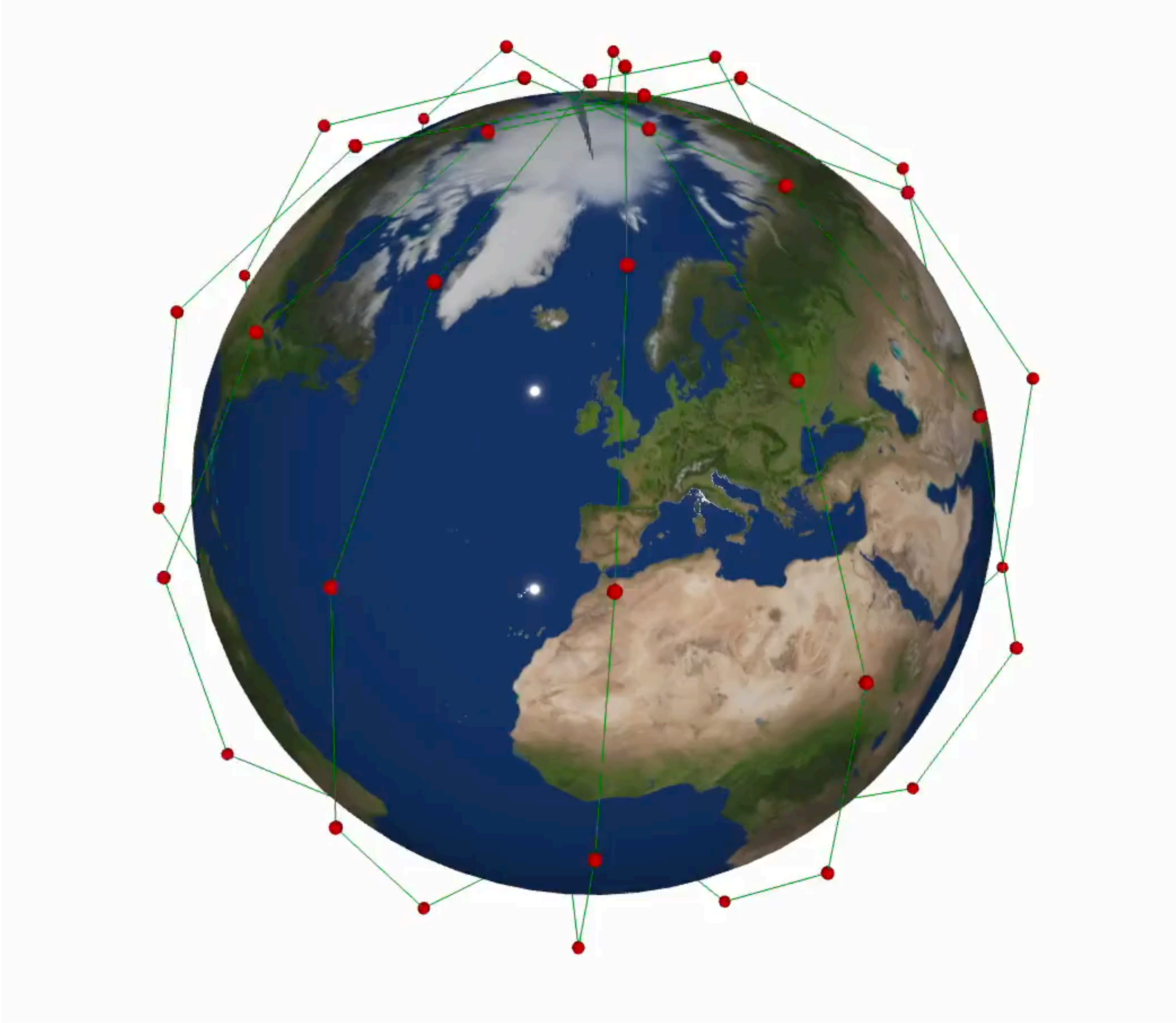
Positions relative to parent orbital bodies



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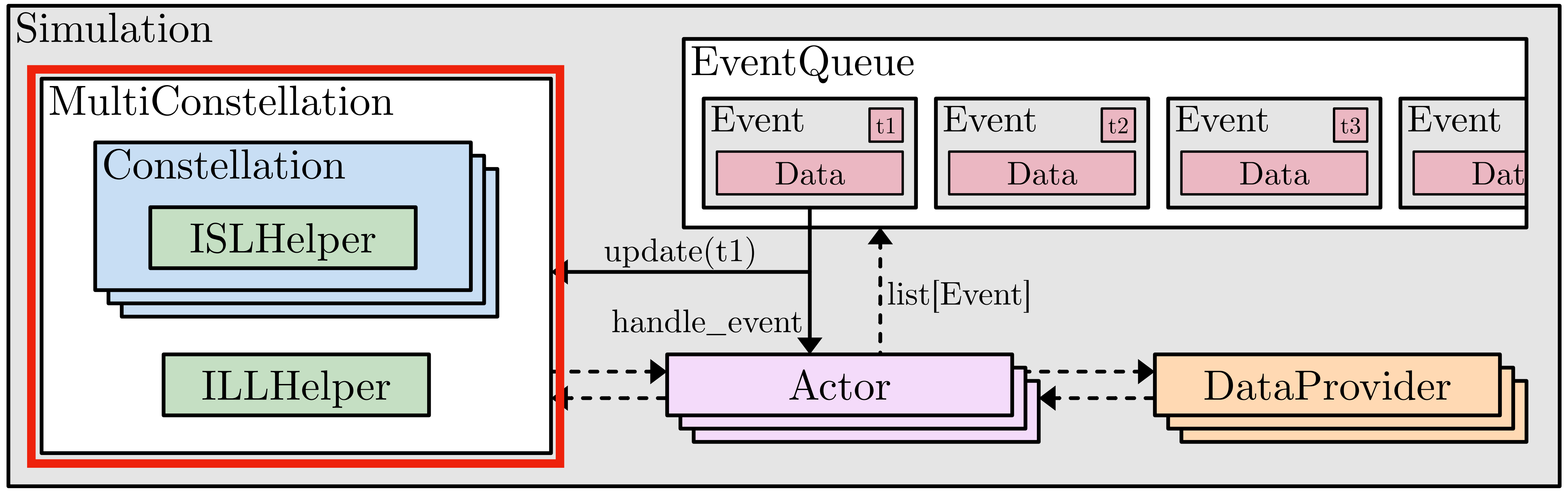

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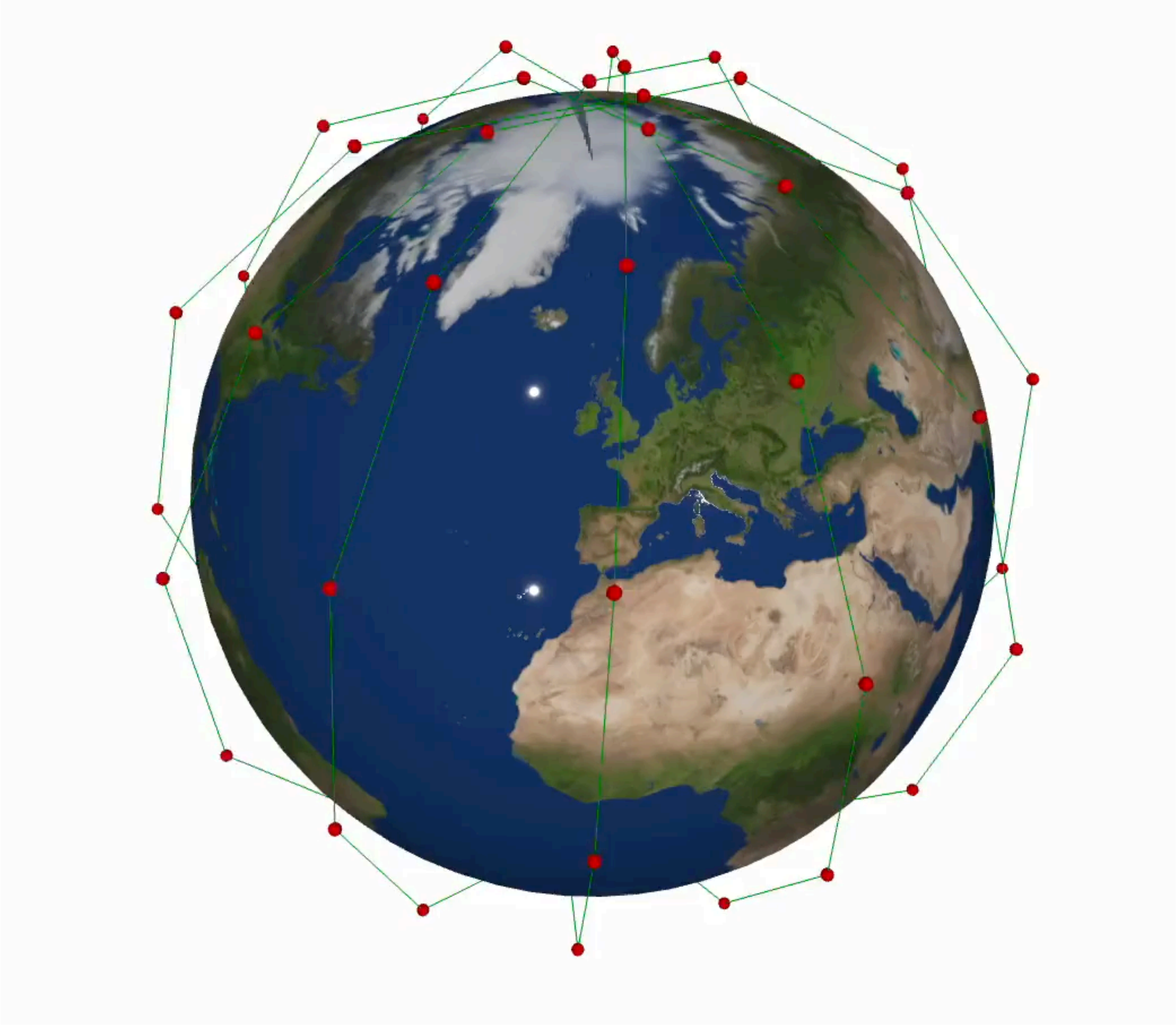
Links computed from distance, line of sight, elevation, occlusion



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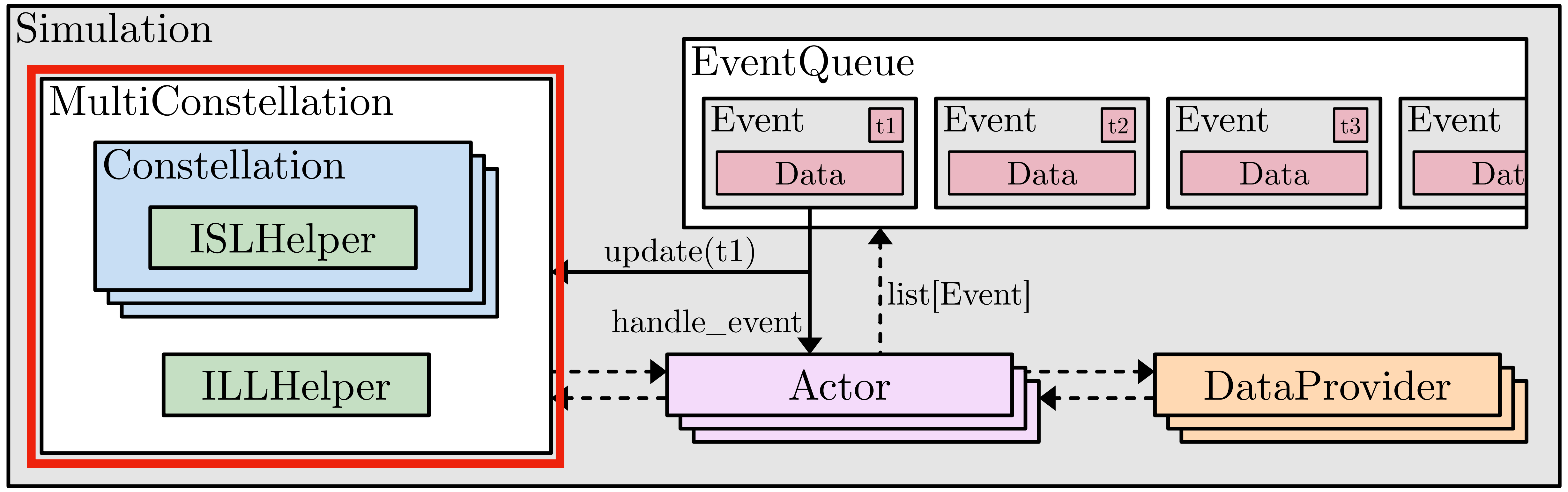

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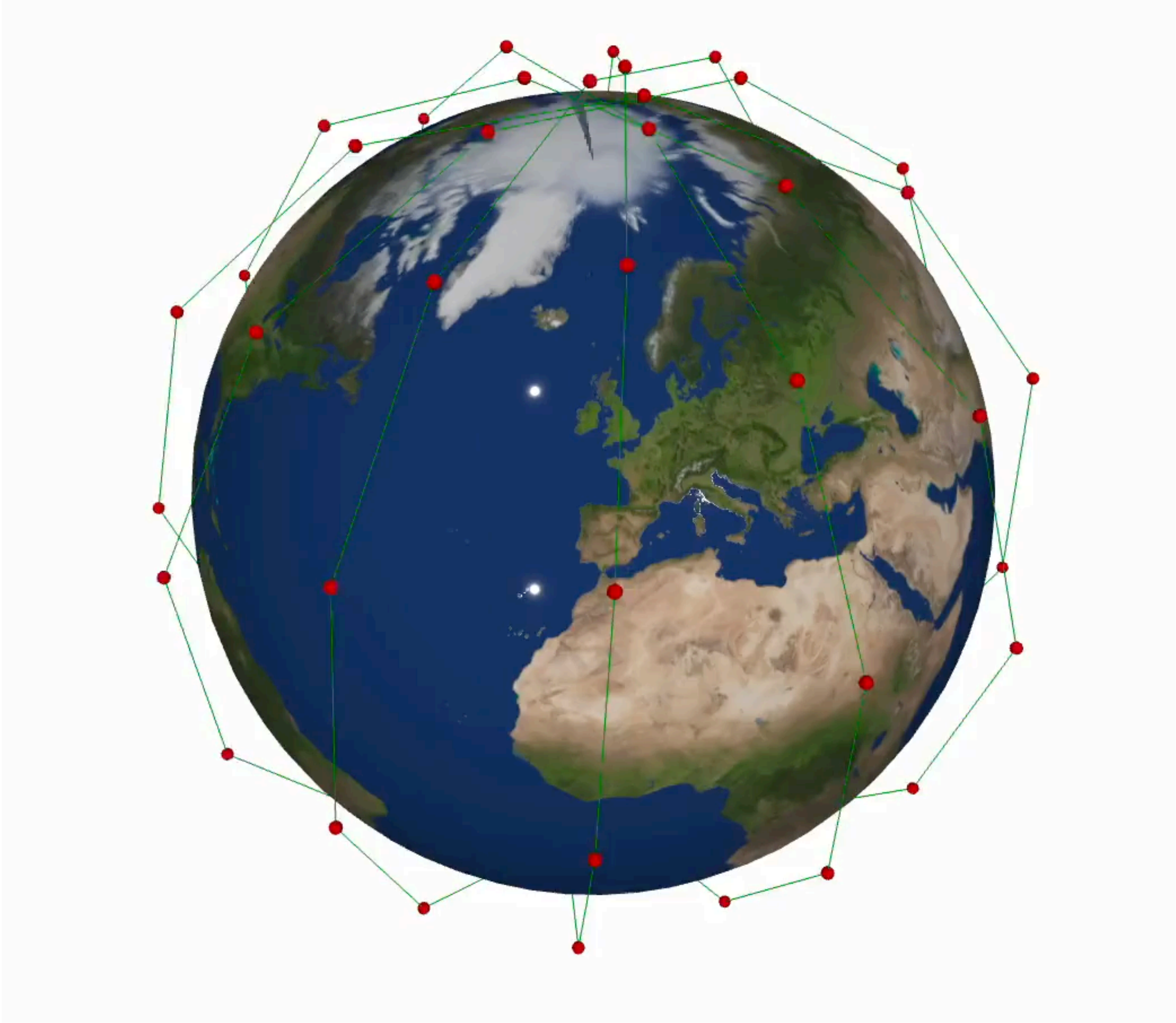
Simplicity that enables immense variety:



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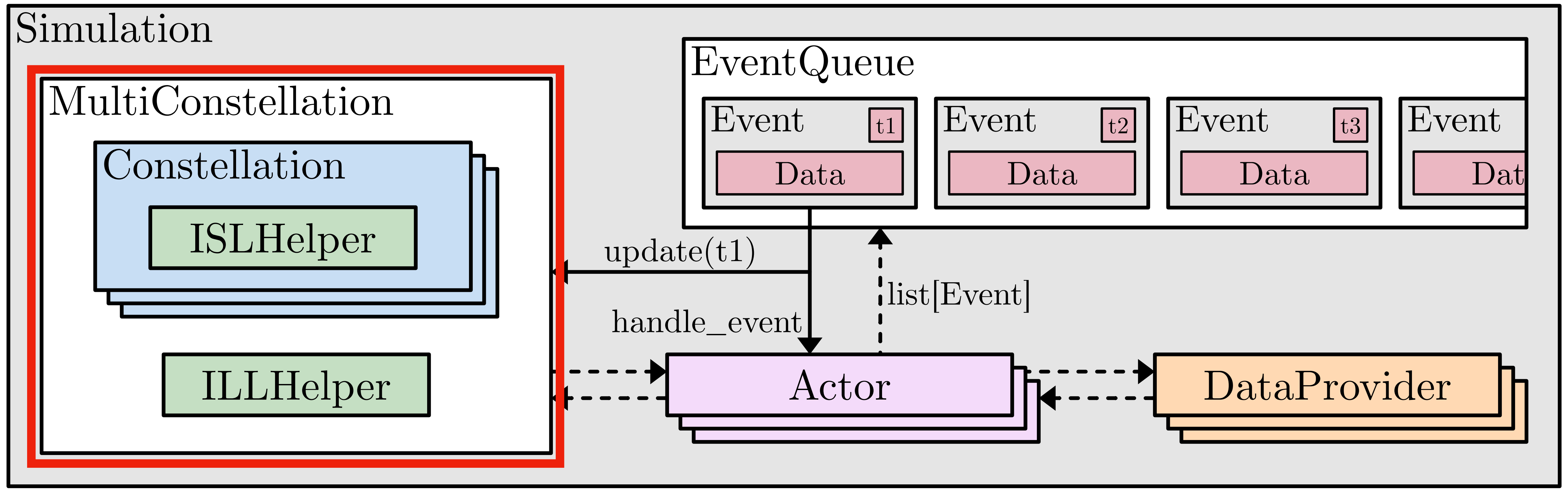

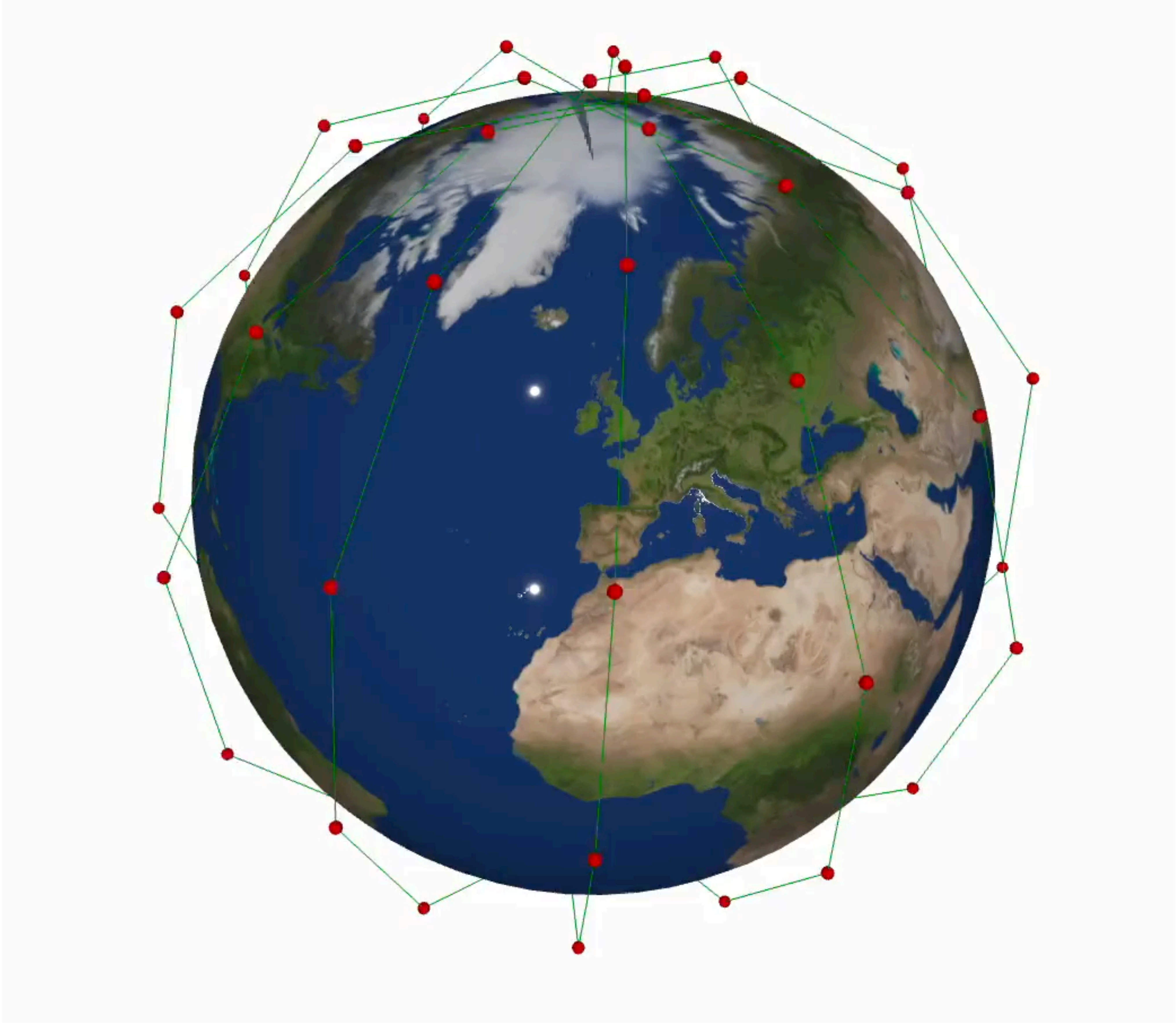

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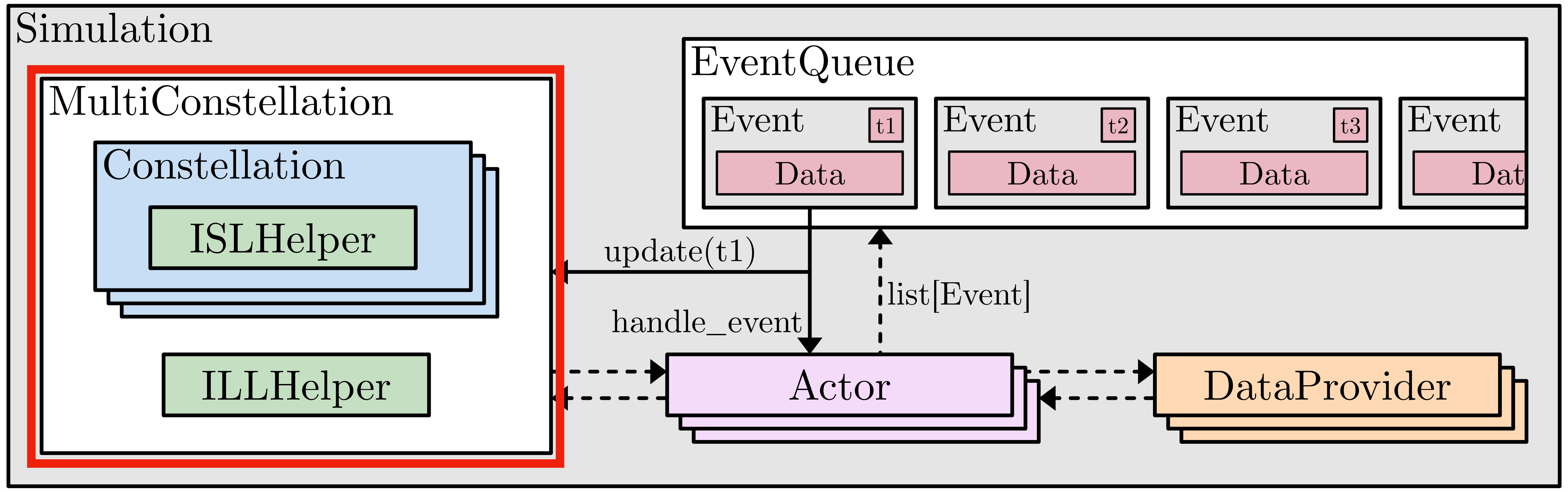

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Simplicity that enables immense variety:

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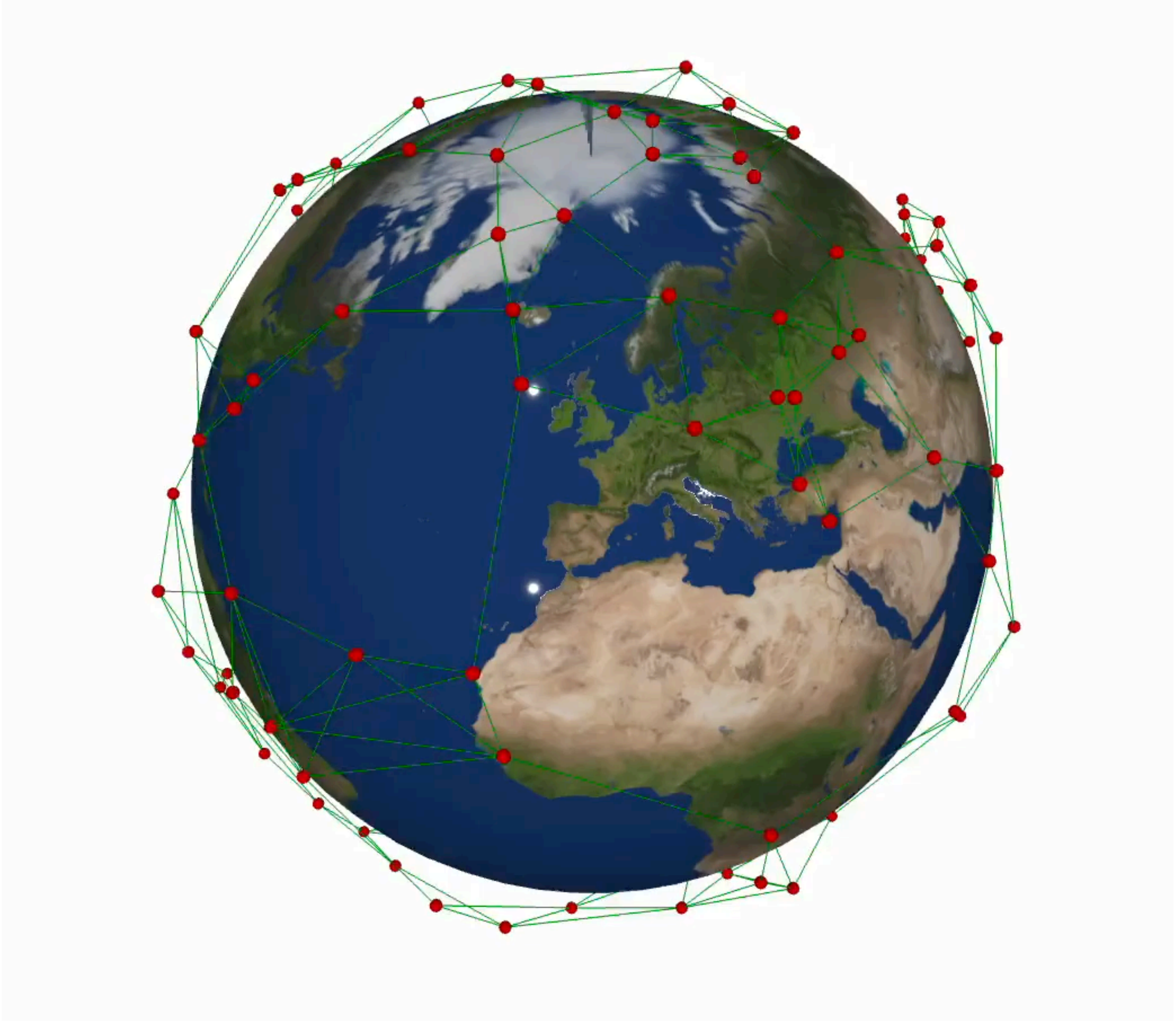
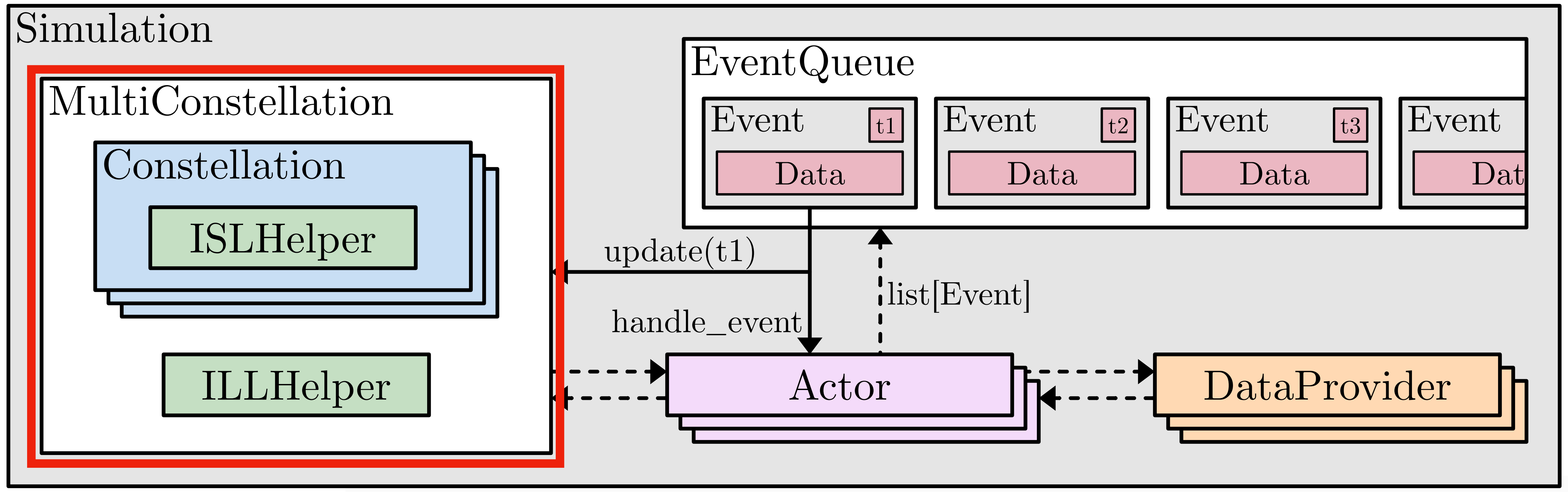
- Networks of CubeSats



Mobility



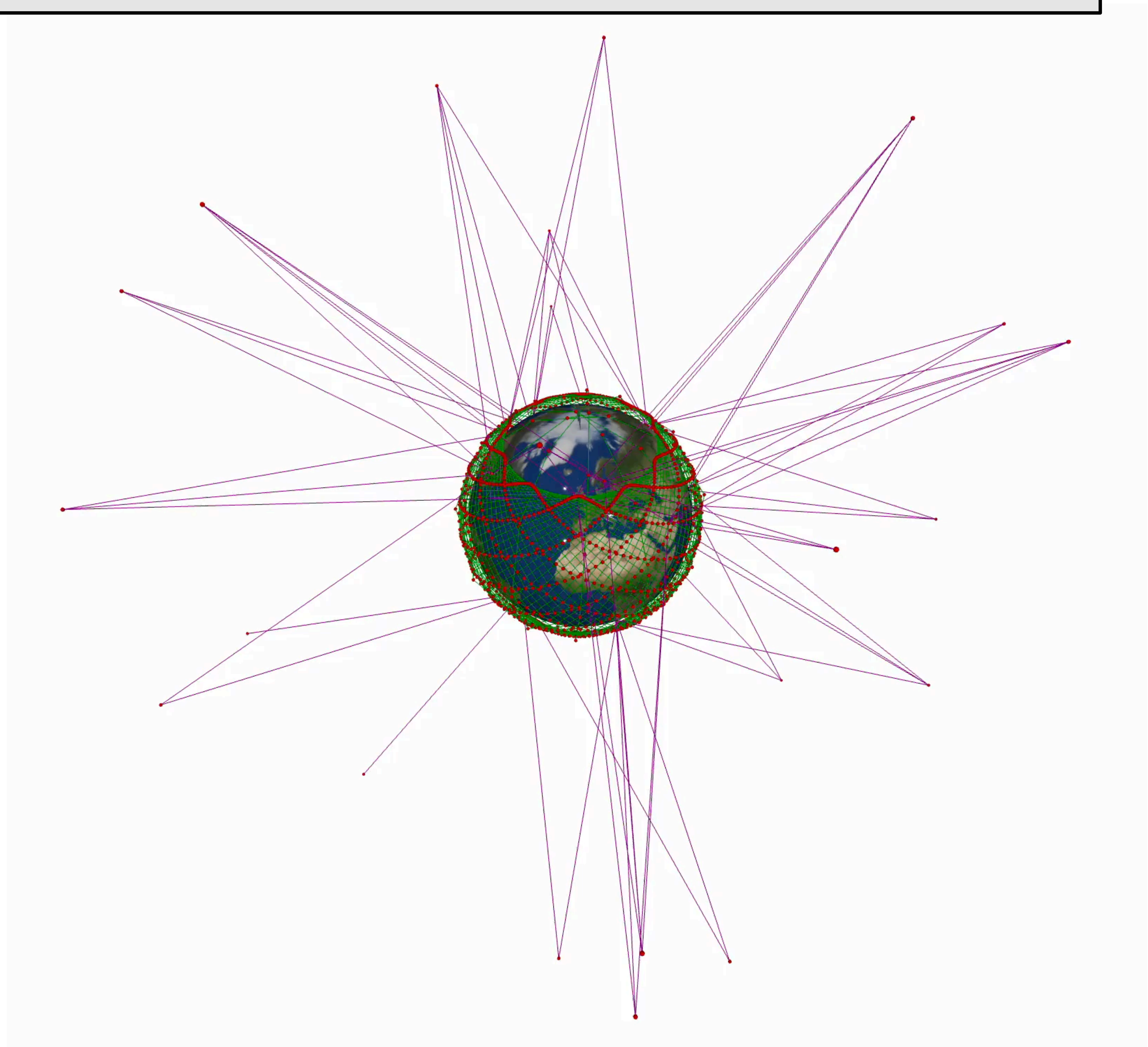
Constellations defined by positions, TLEs, Walker definitions, or arbitrary functions

Positions relative to parent orbital bodies

Links computed from distance, line of sight, elevation, occlusion

Simplicity that enables immense variety:

- Earth constellations
- Networks of CubeSats
- Federation of constellations



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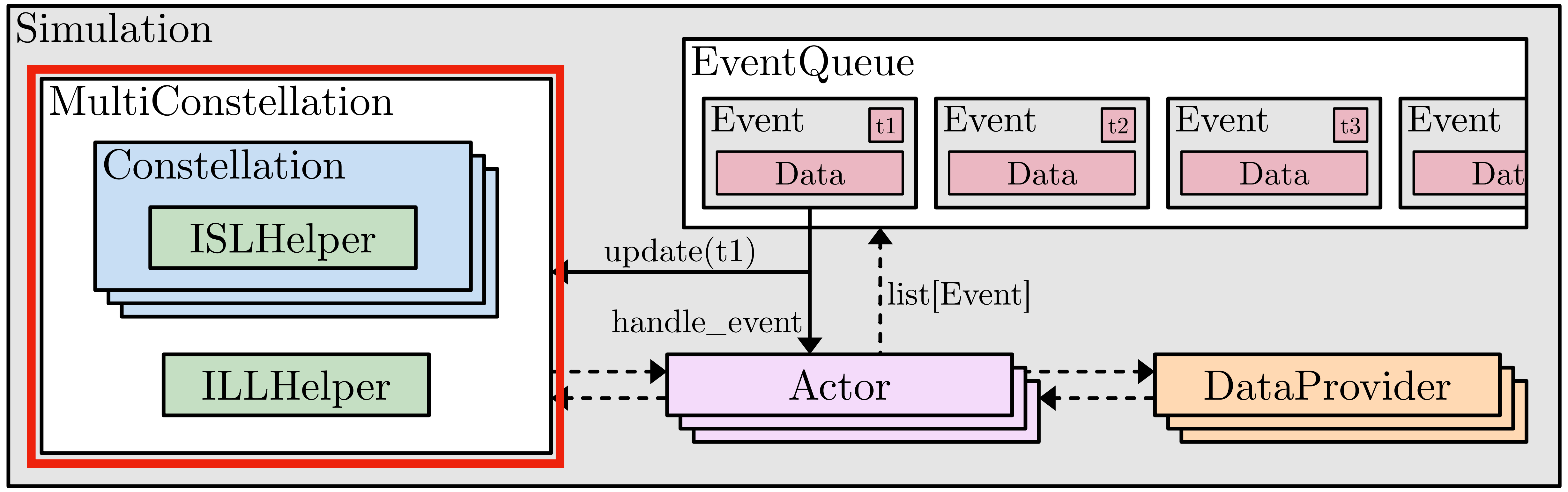

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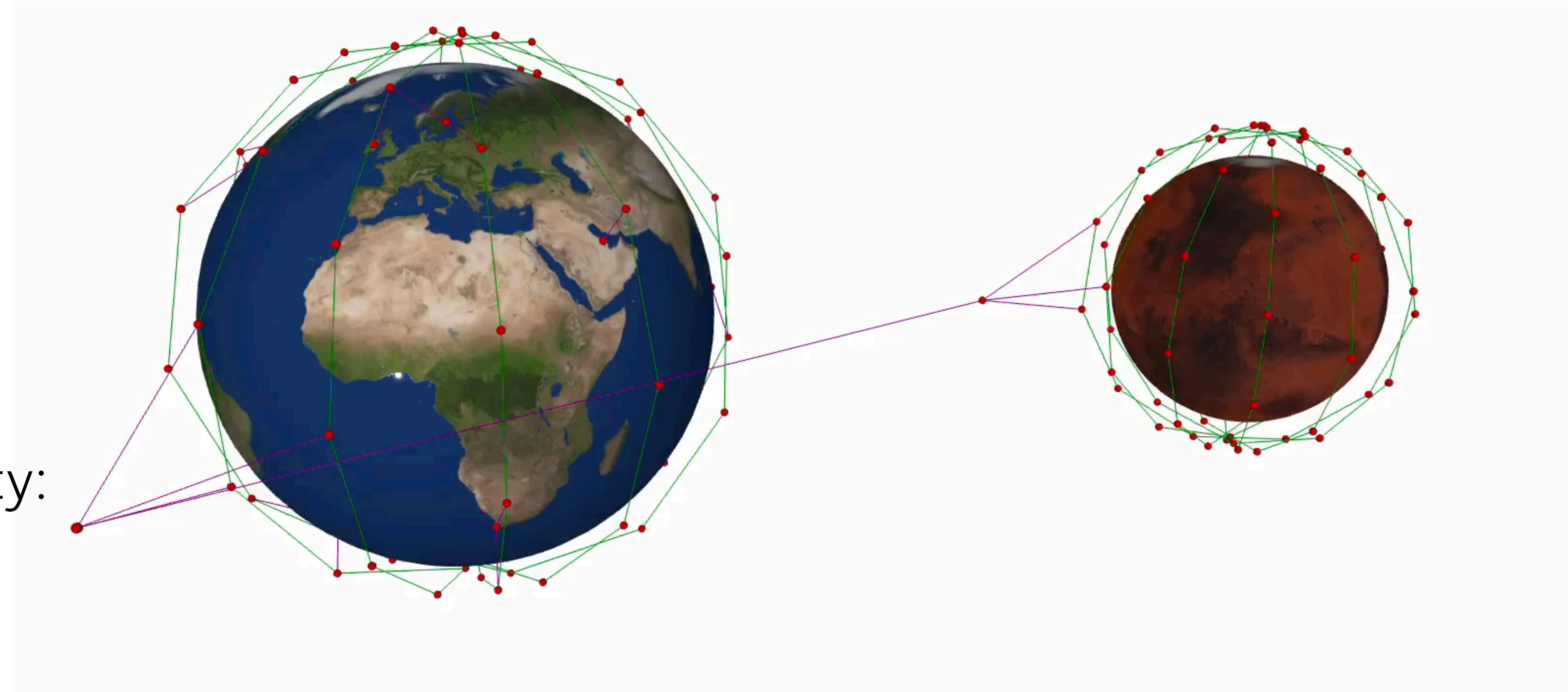

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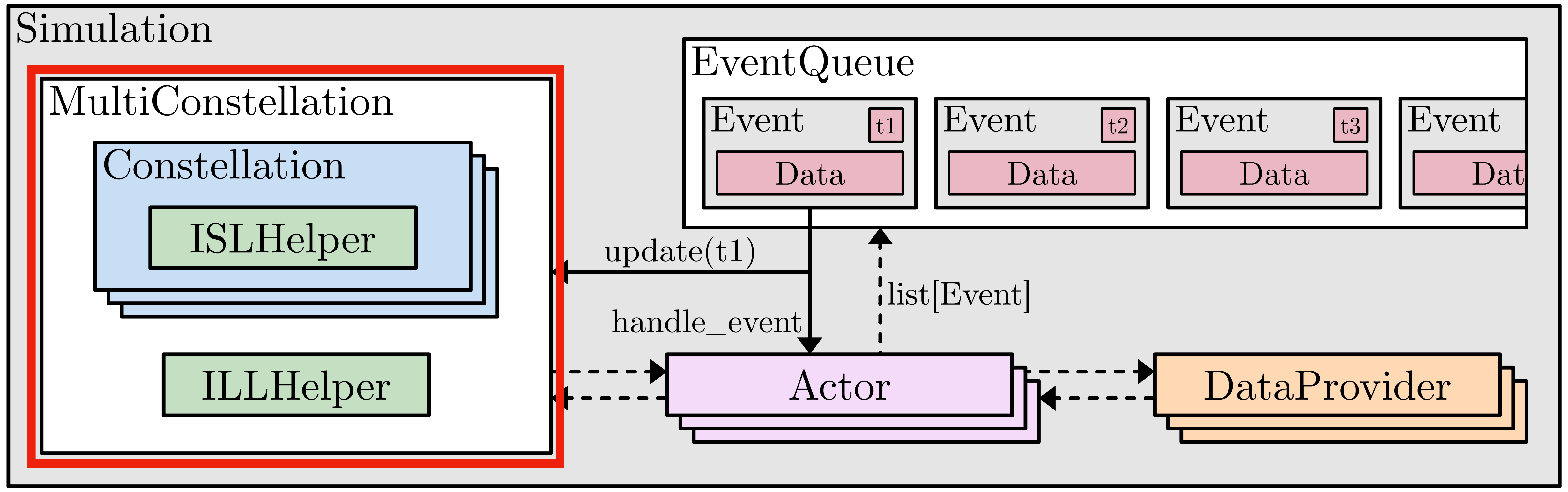

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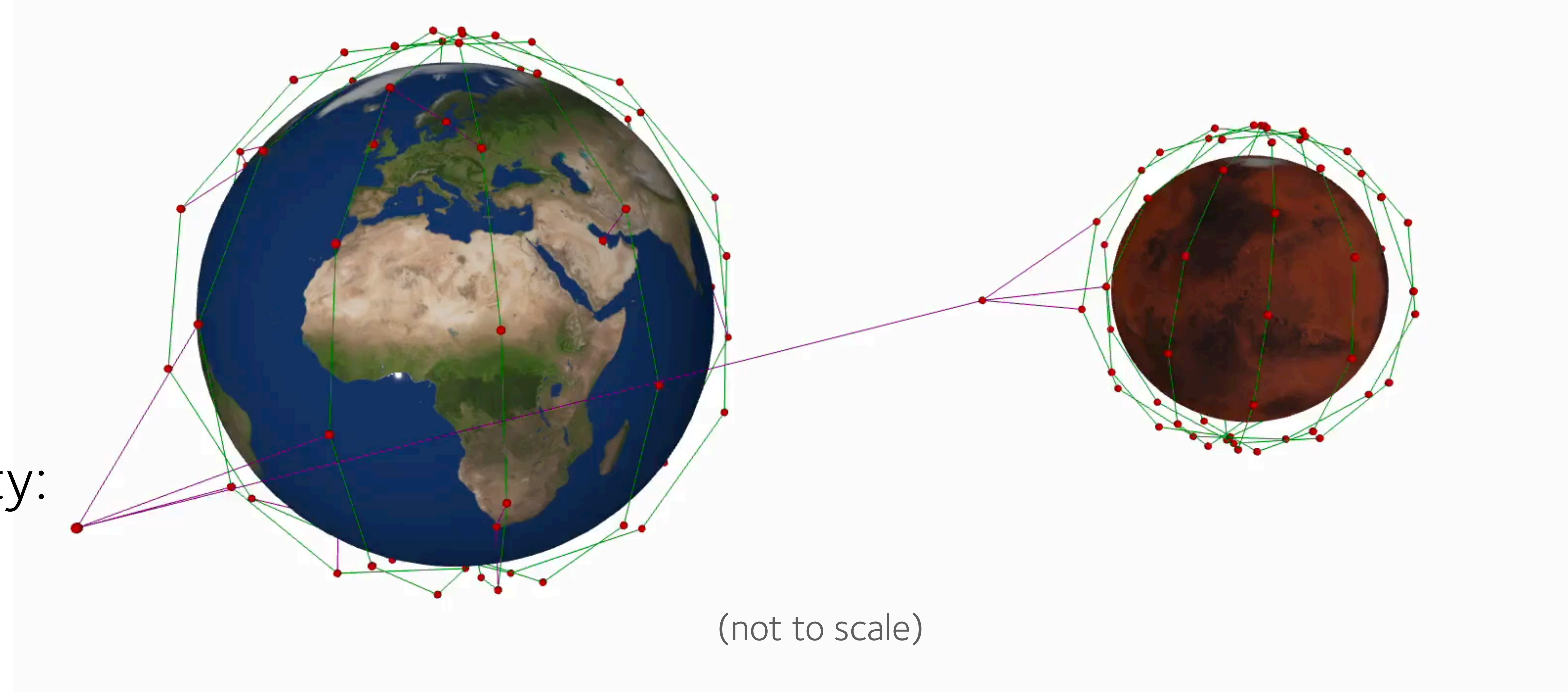

MESSAGE DELIVERY/ROUTING

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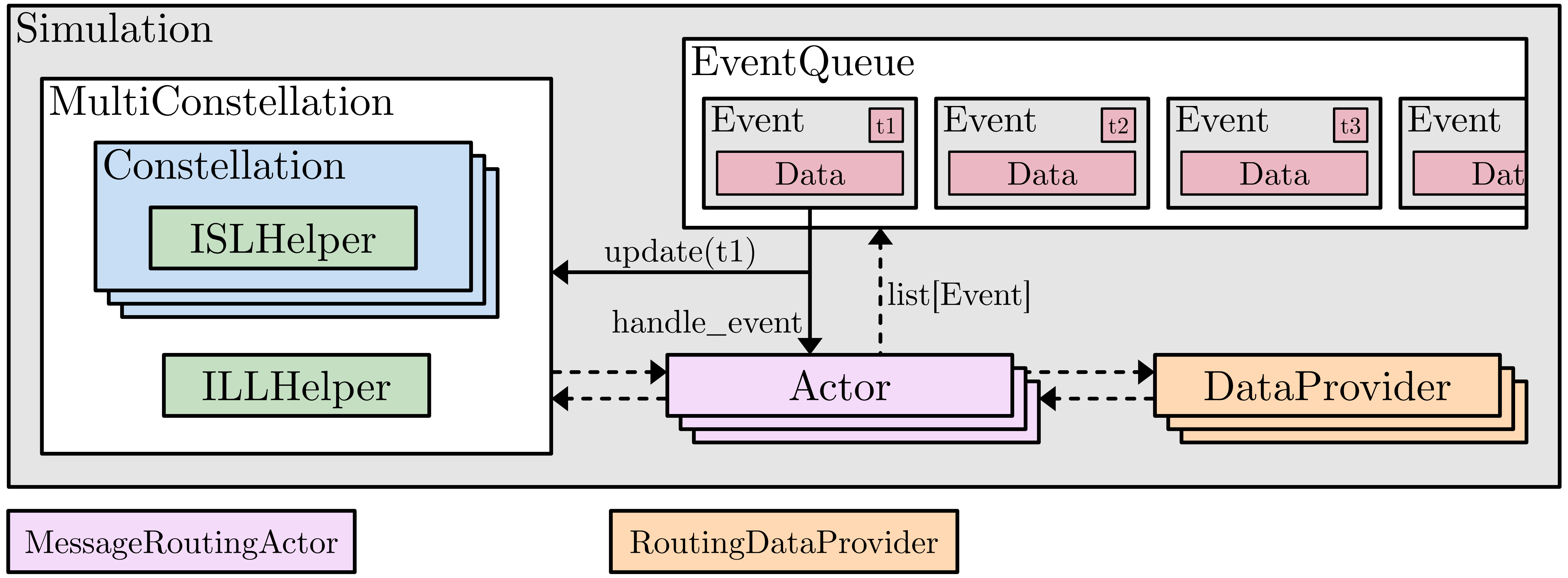
- Query routing module for information



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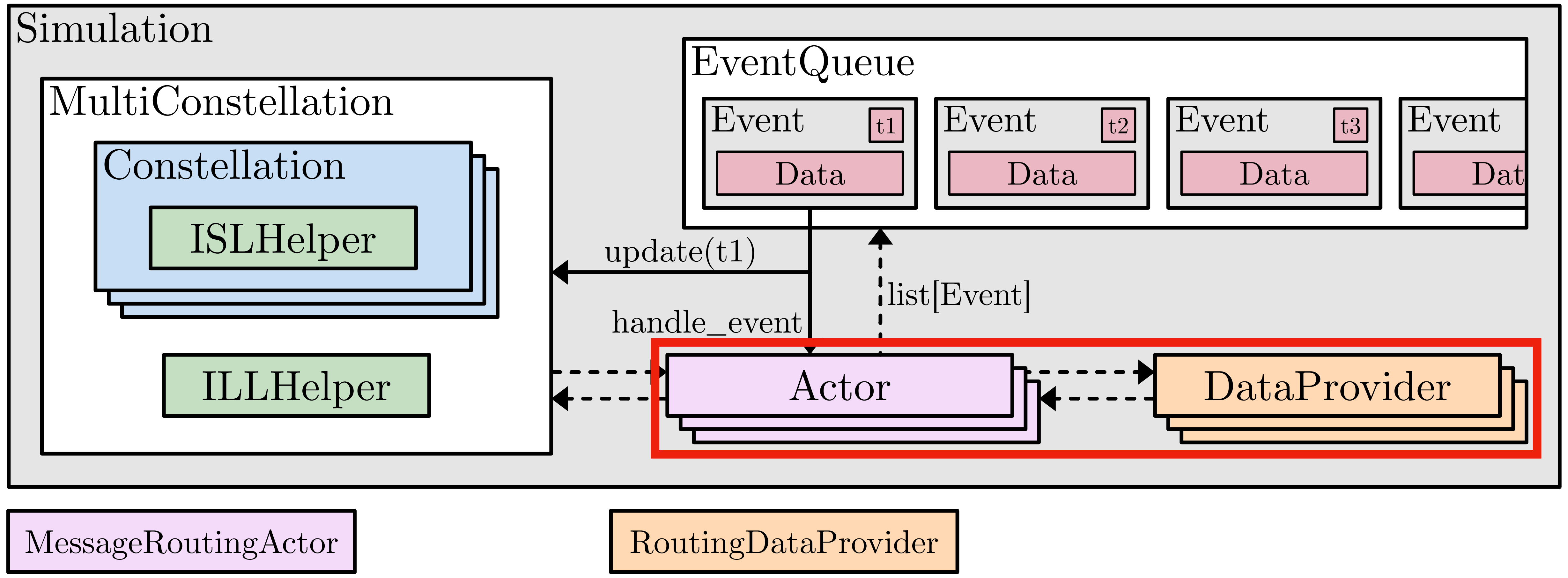

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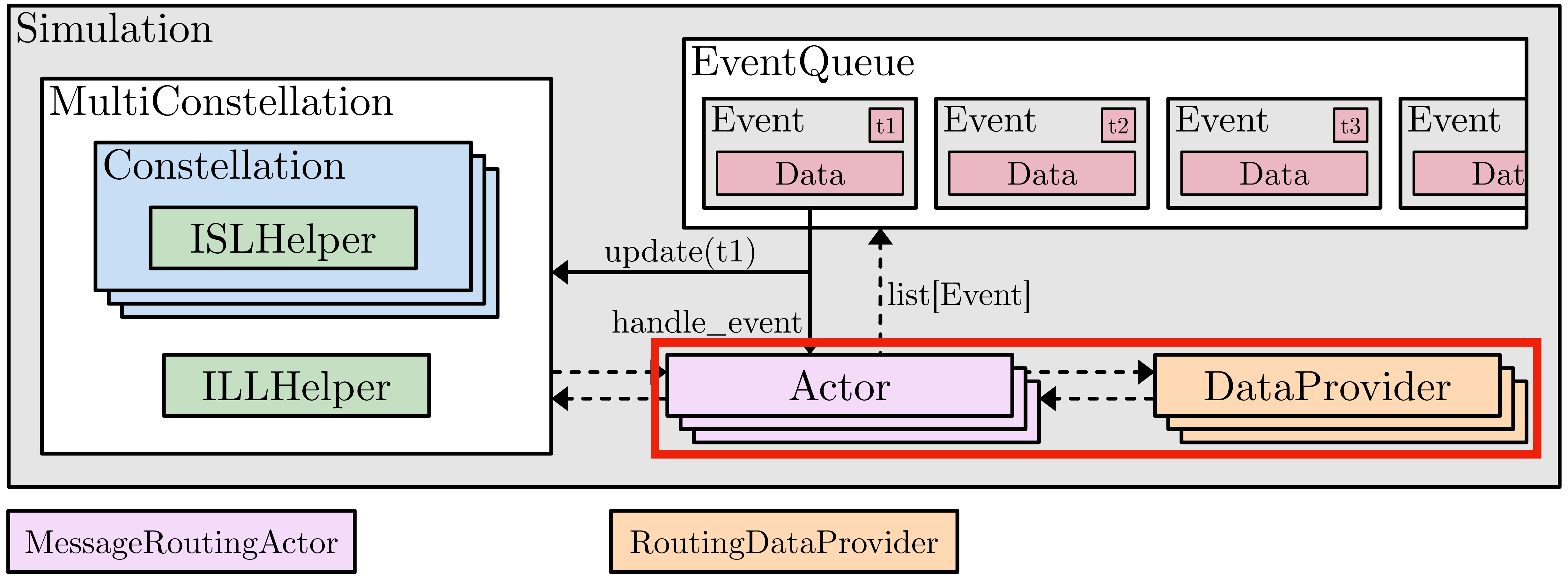

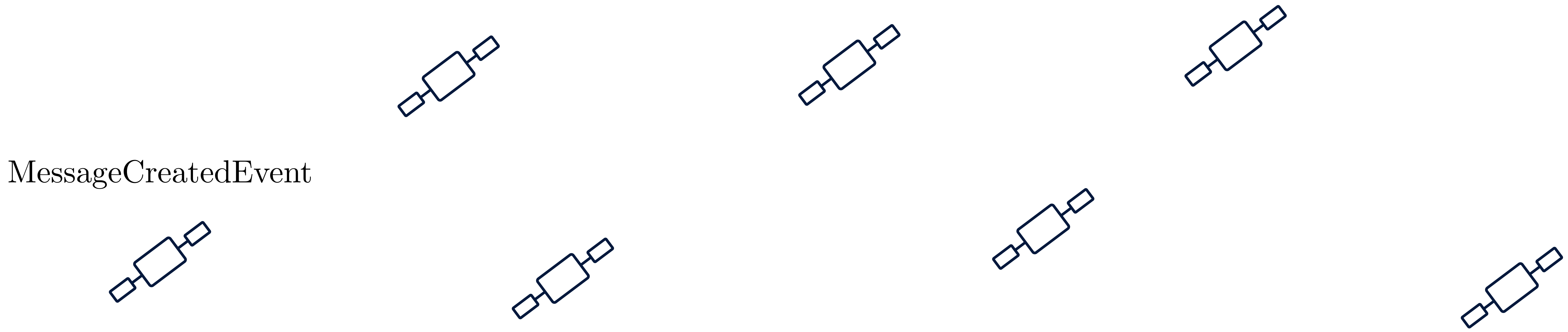

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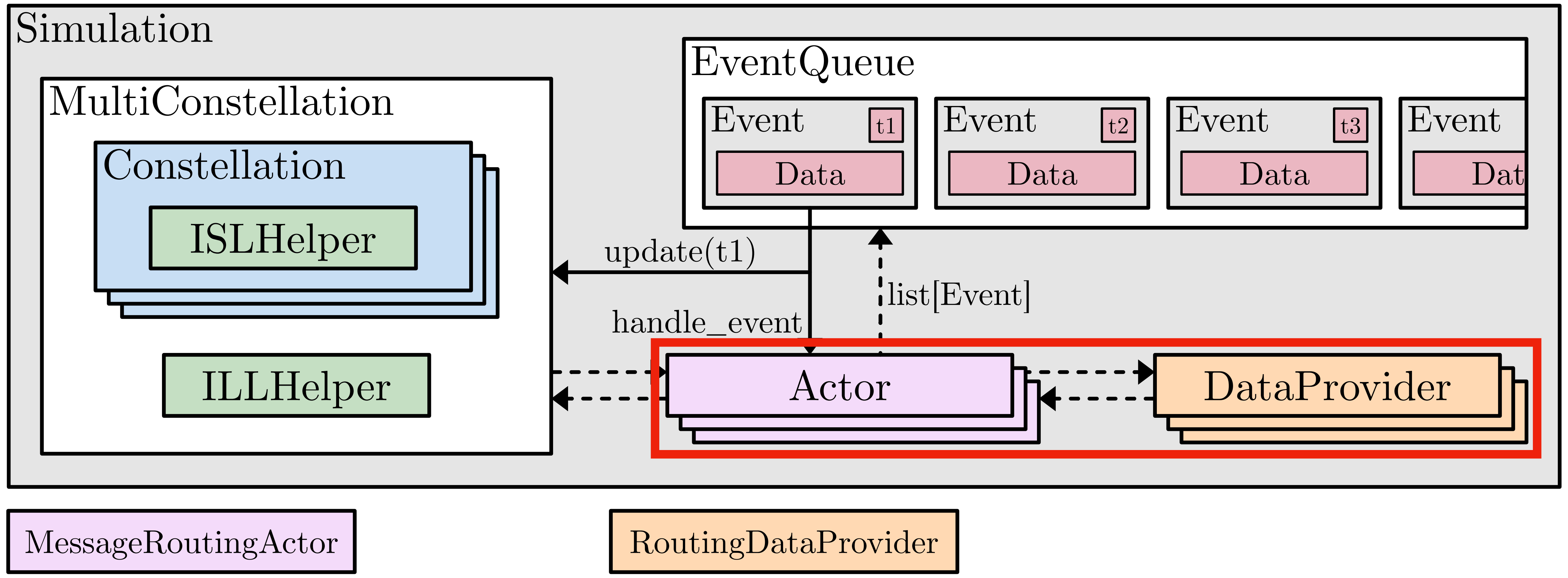

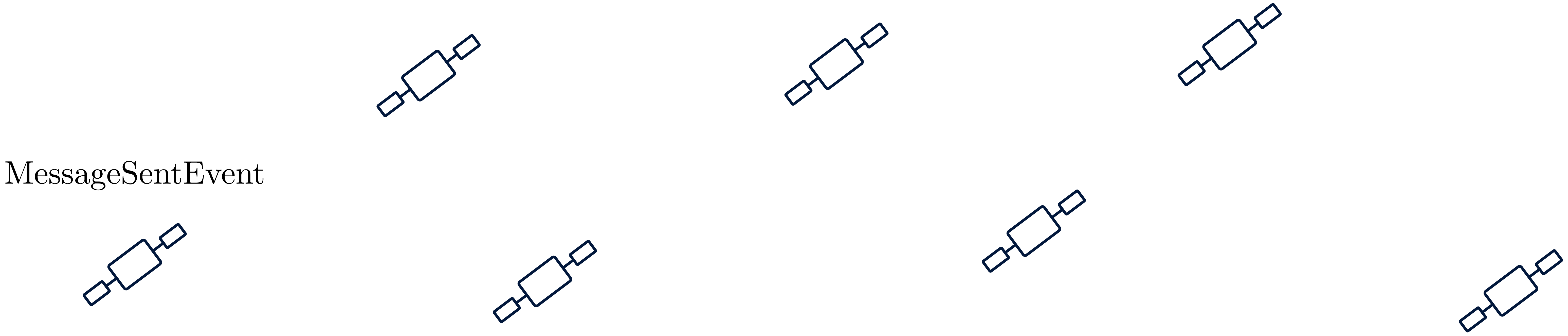

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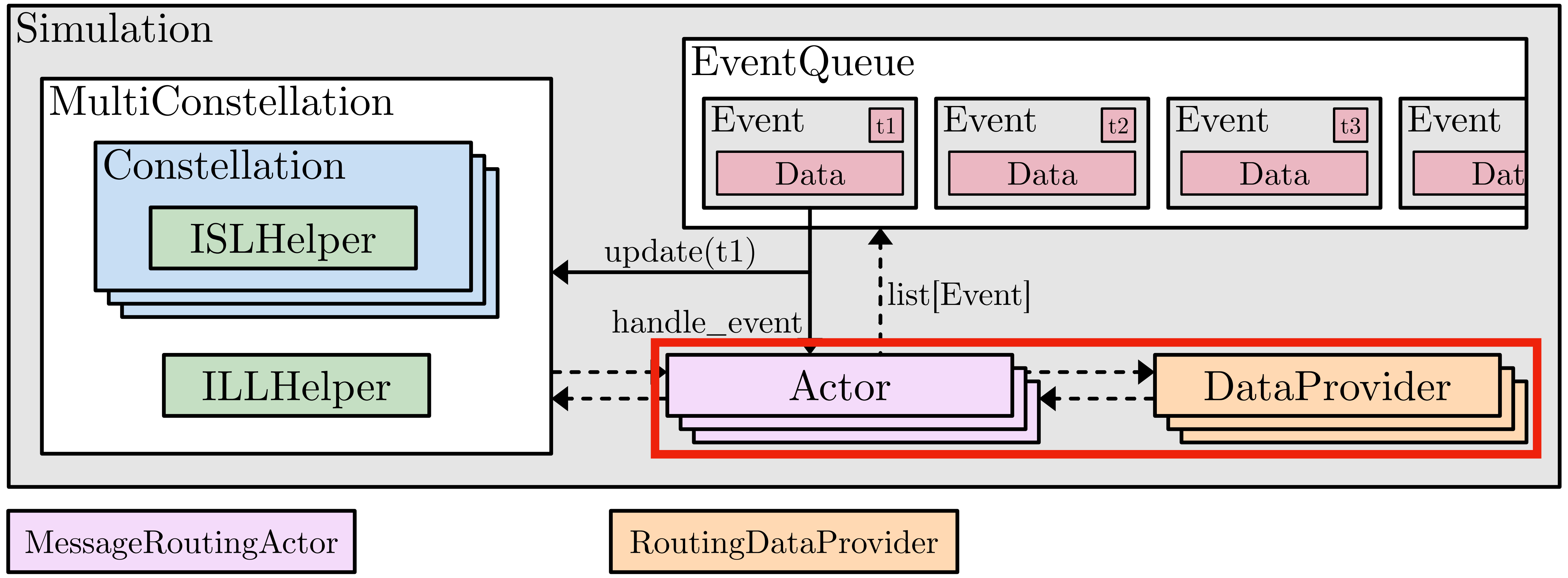

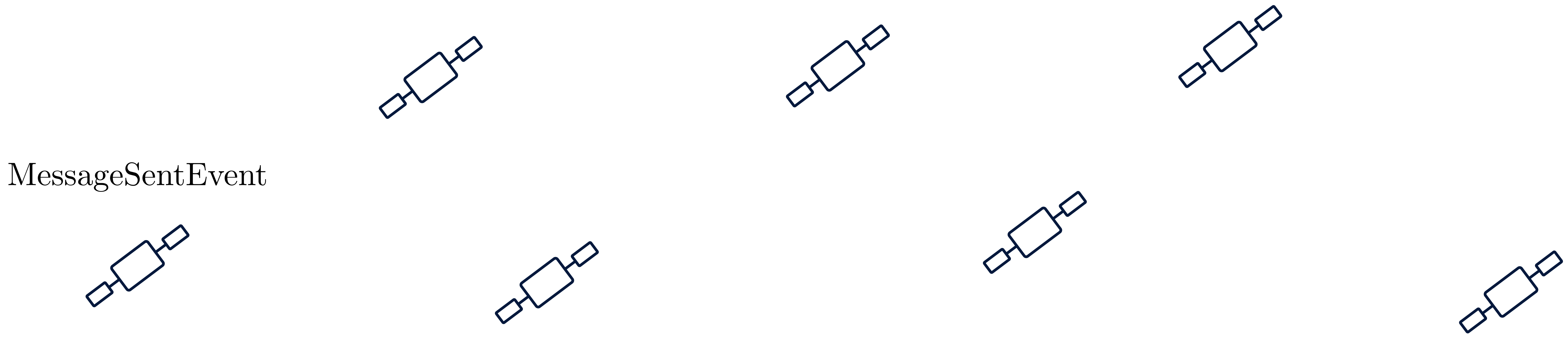

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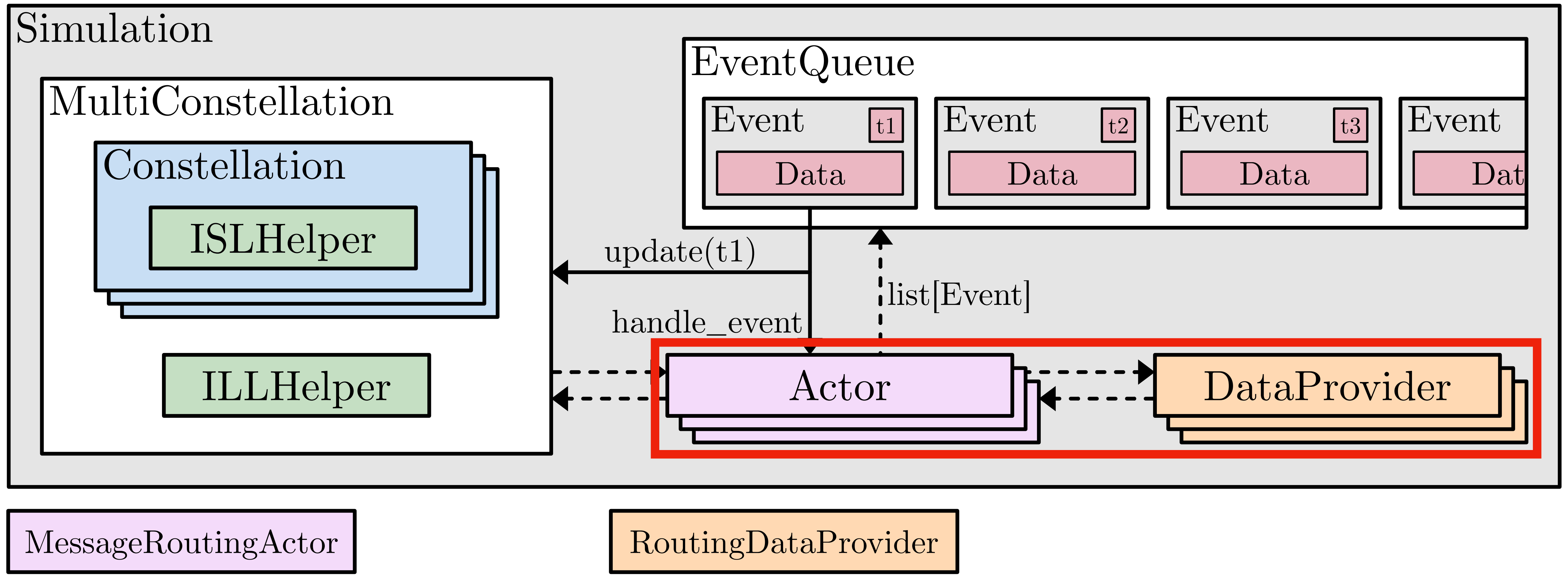

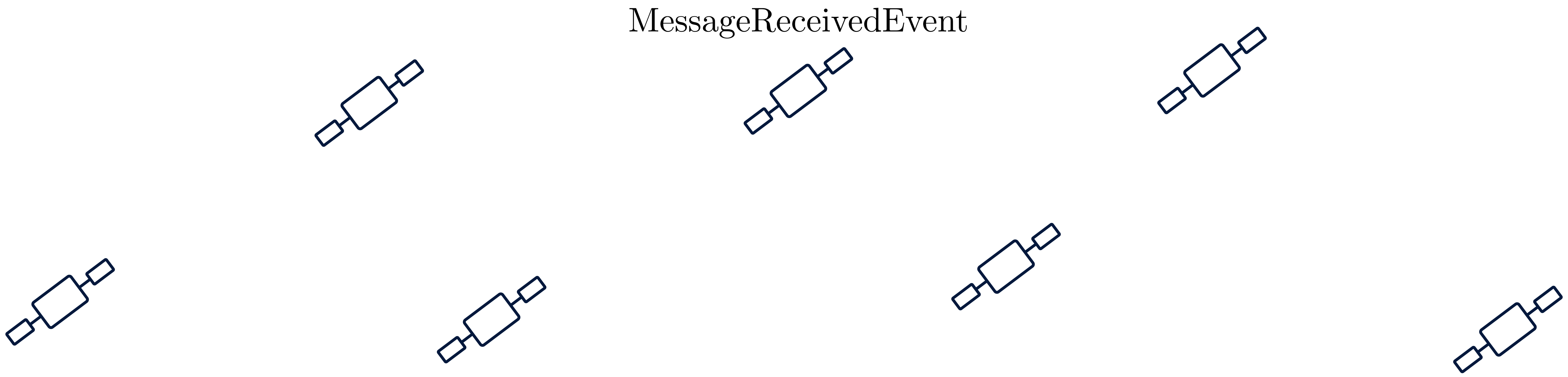

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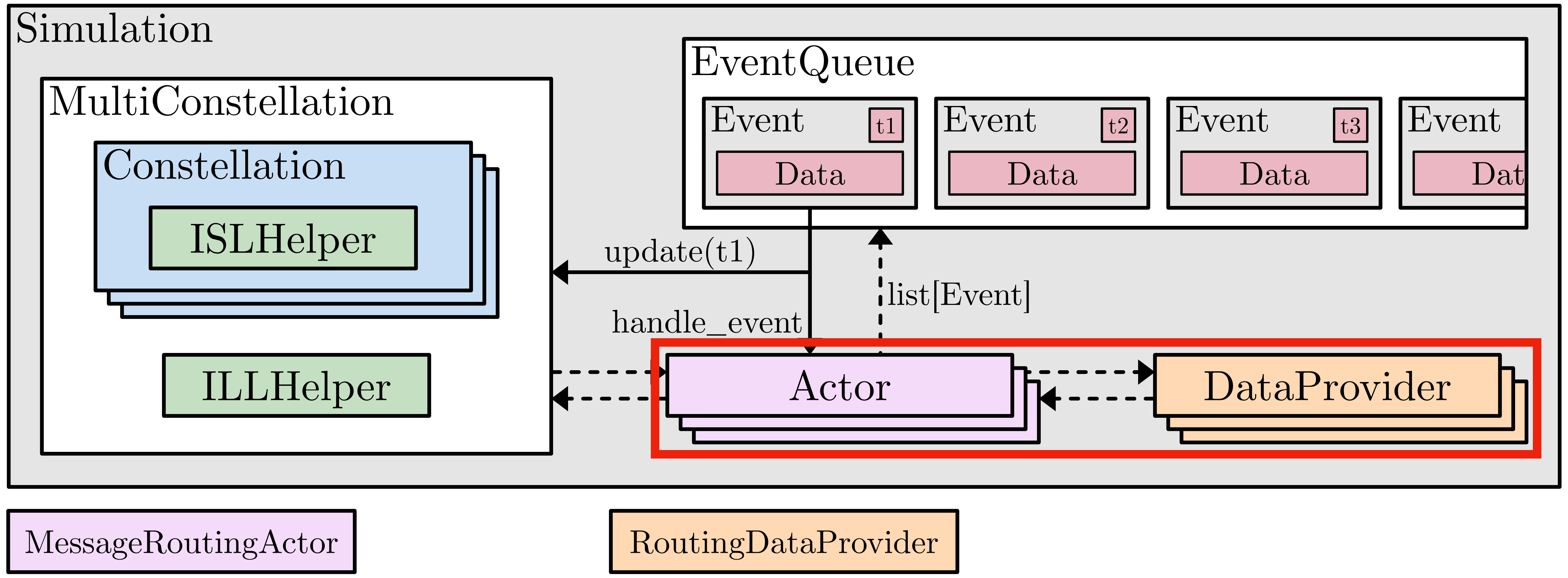

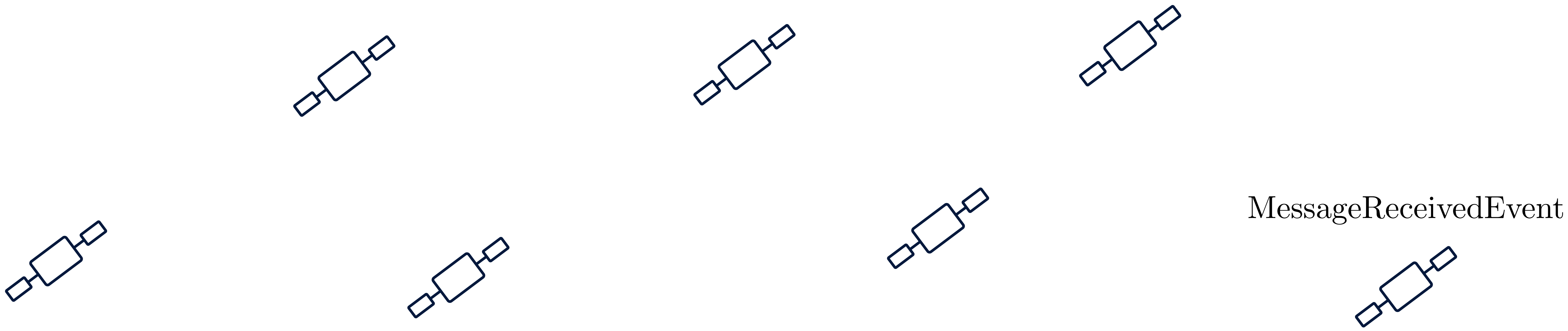

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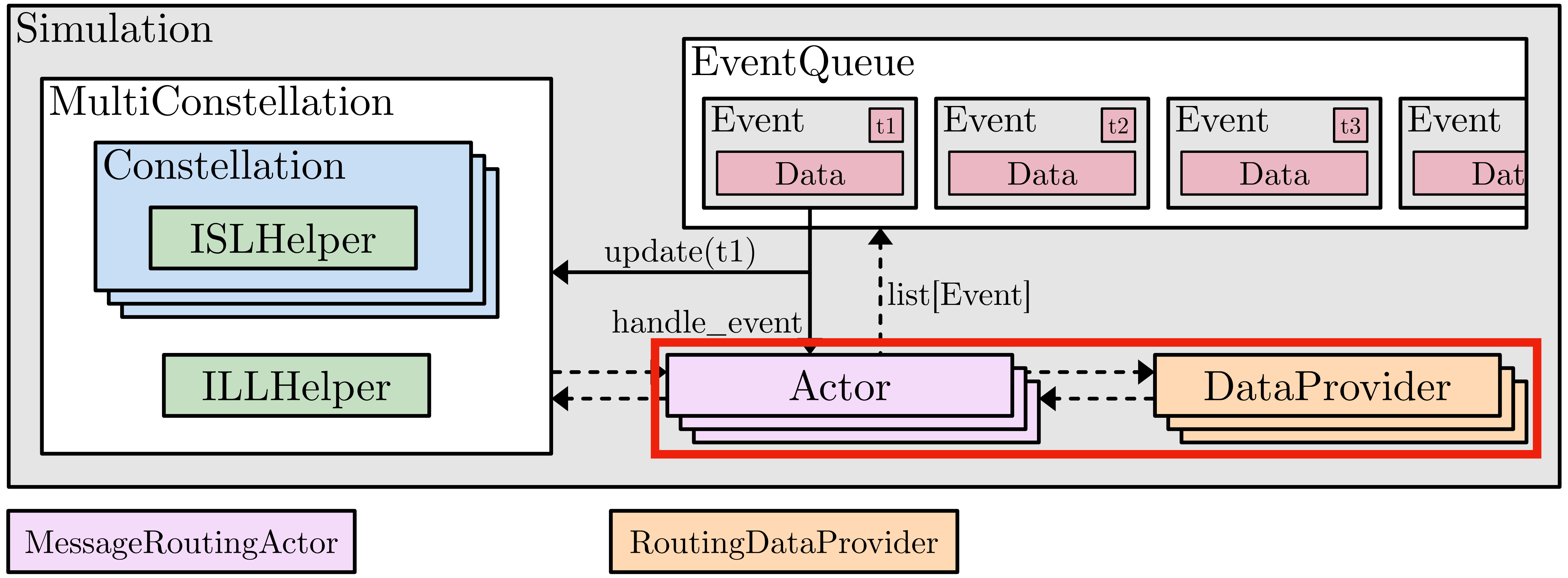

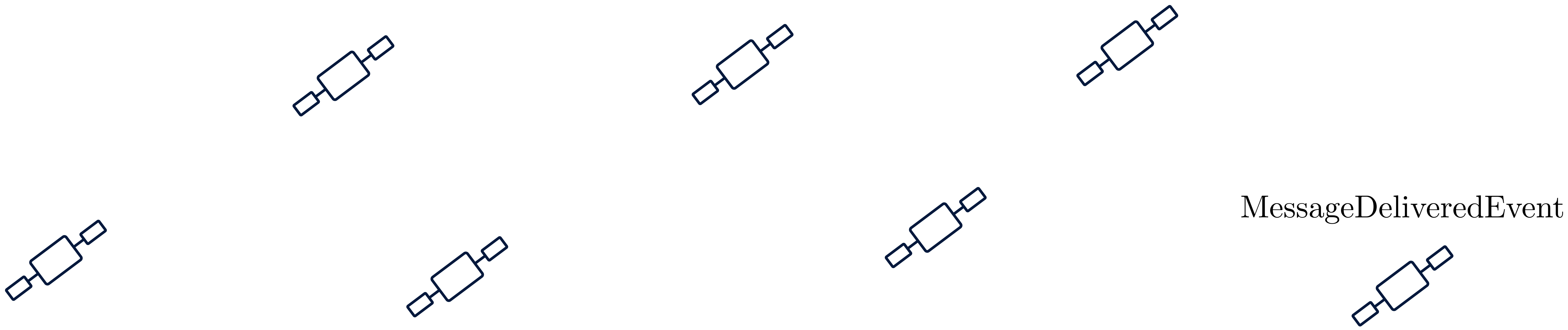

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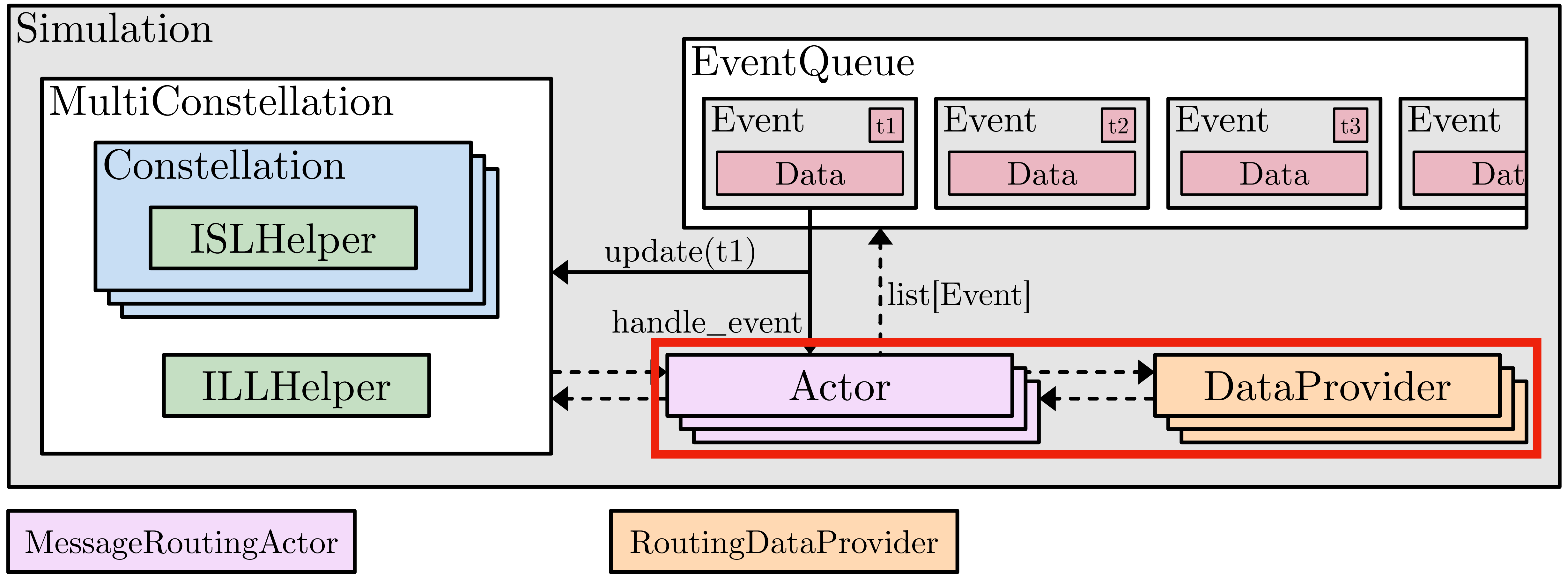

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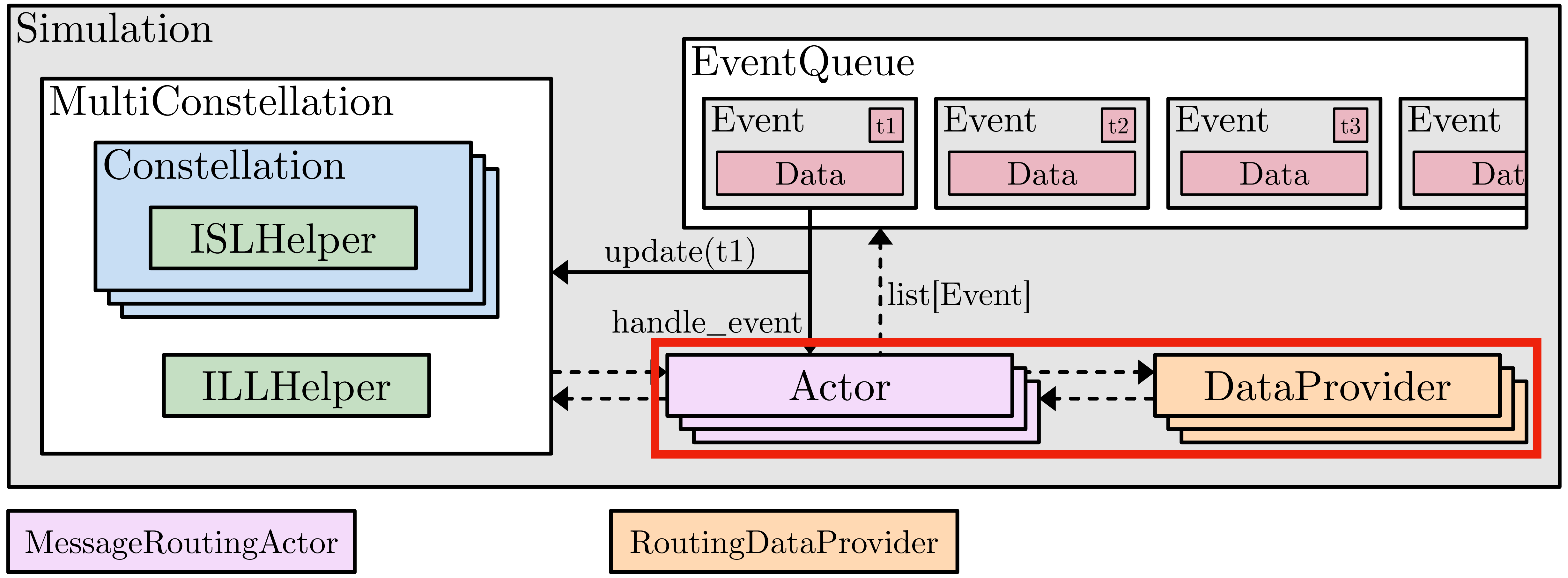

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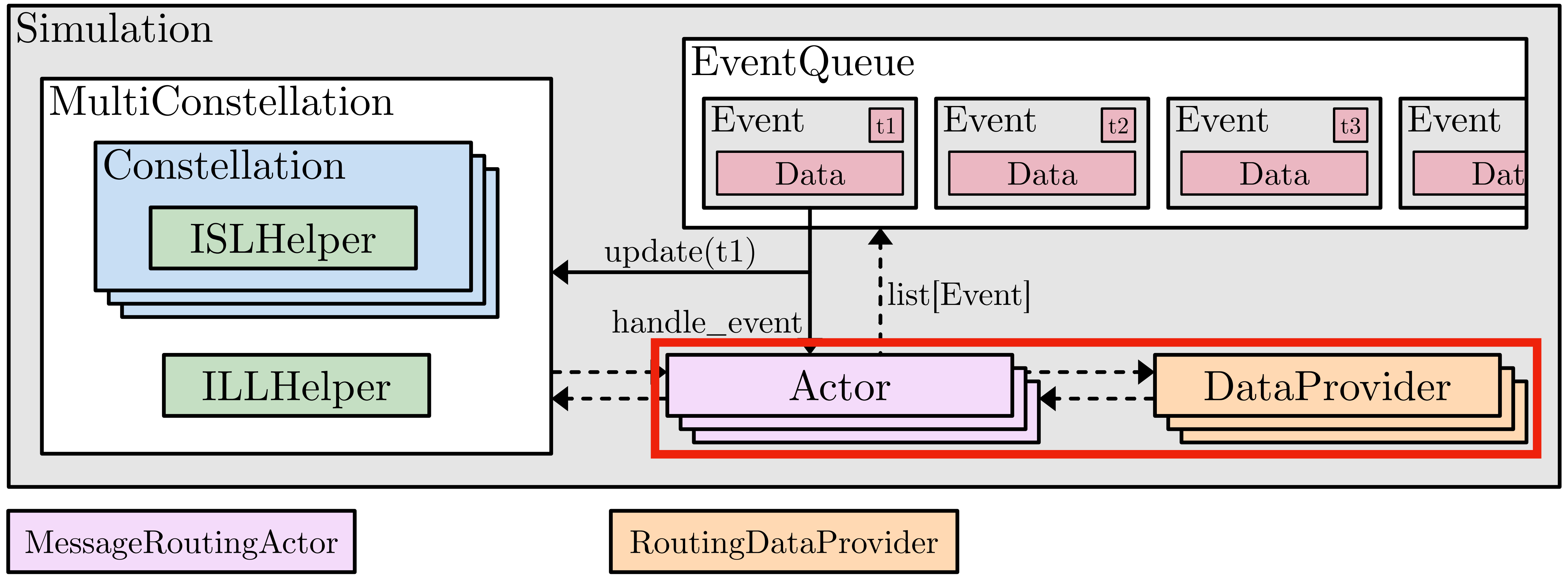

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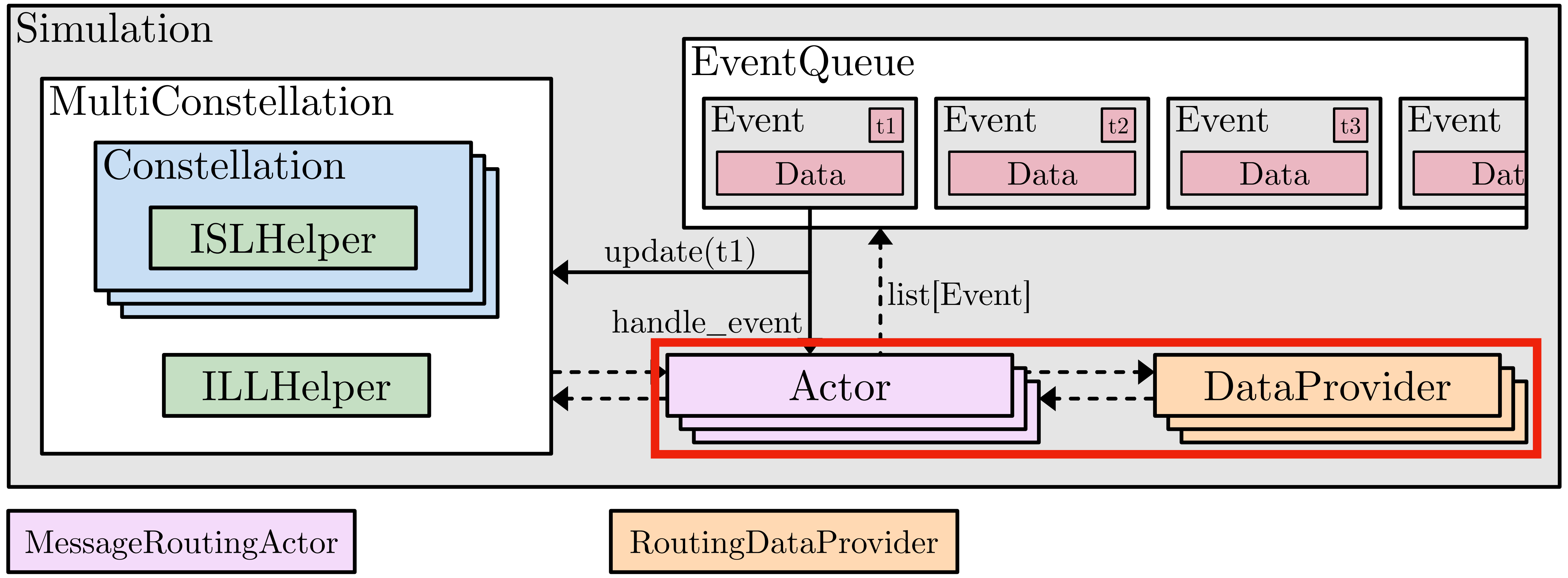

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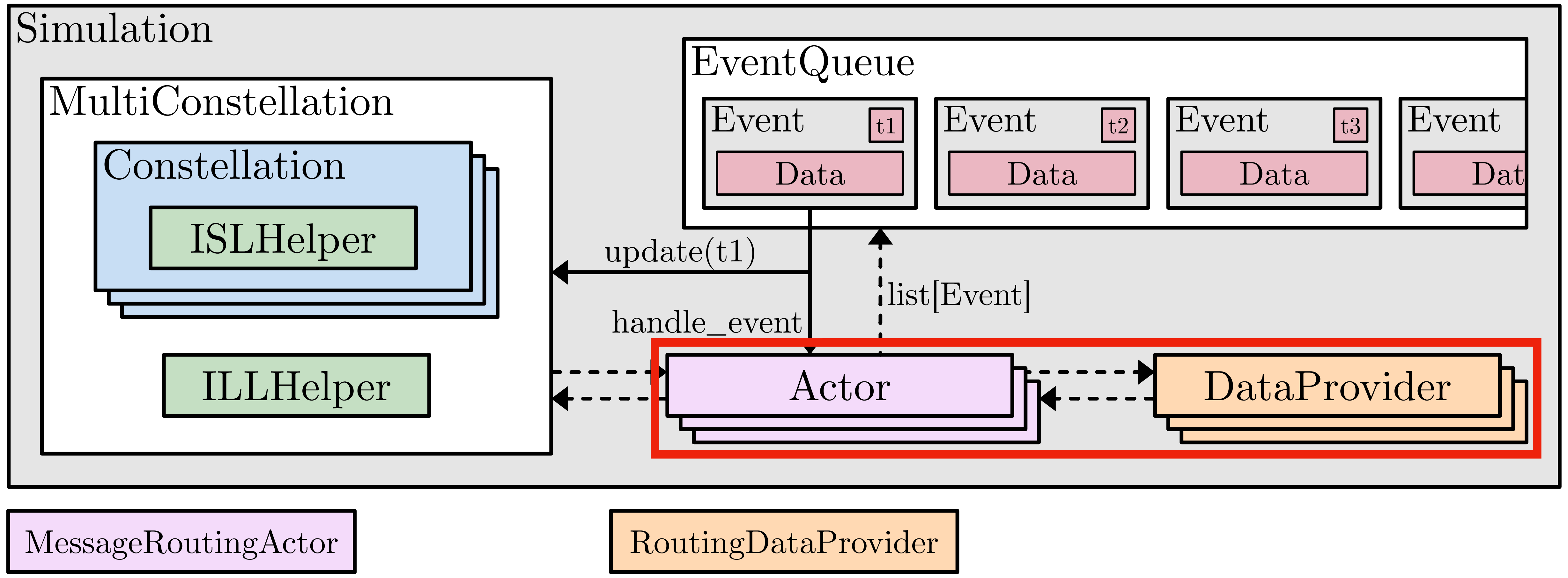

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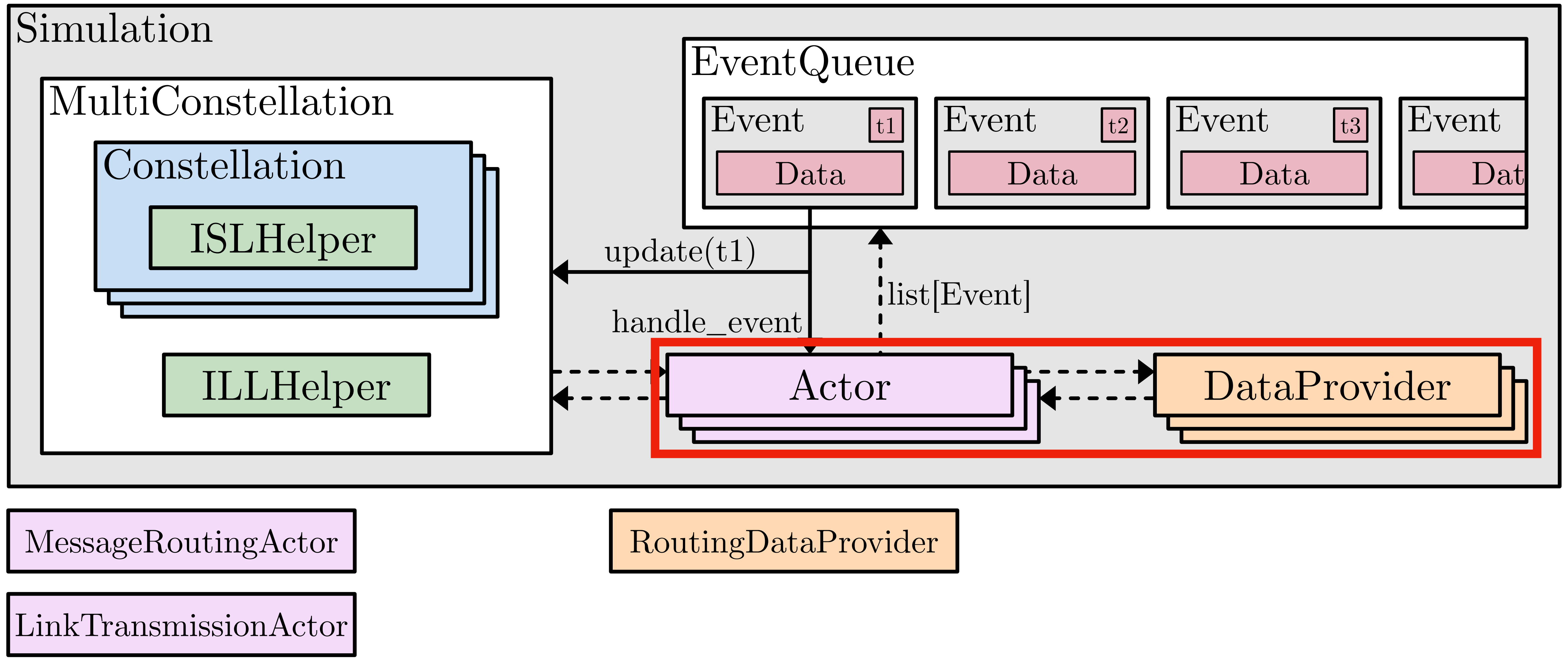

Message Delivery/Routing

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- LinkTransmissionActor adds message size and bandwidth
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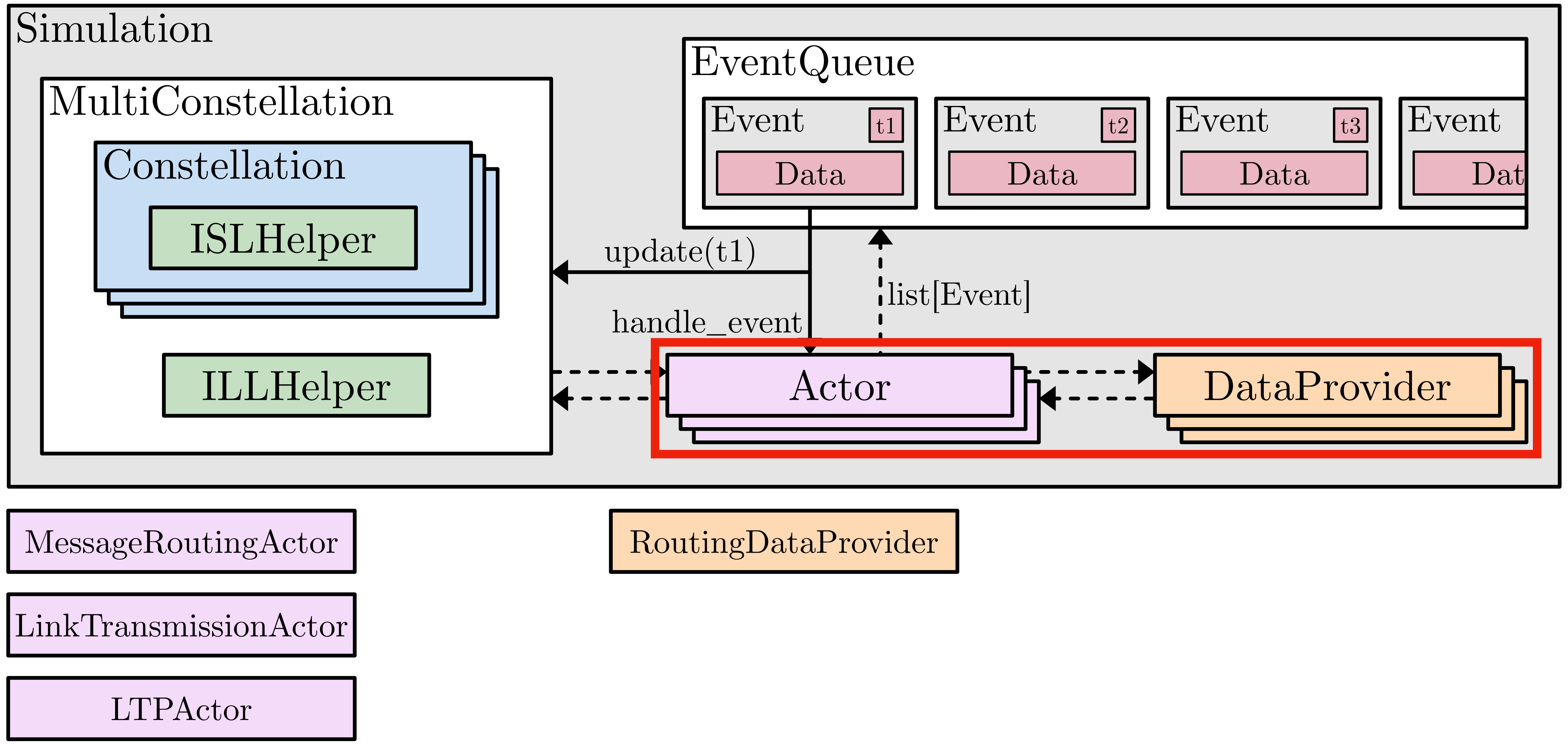

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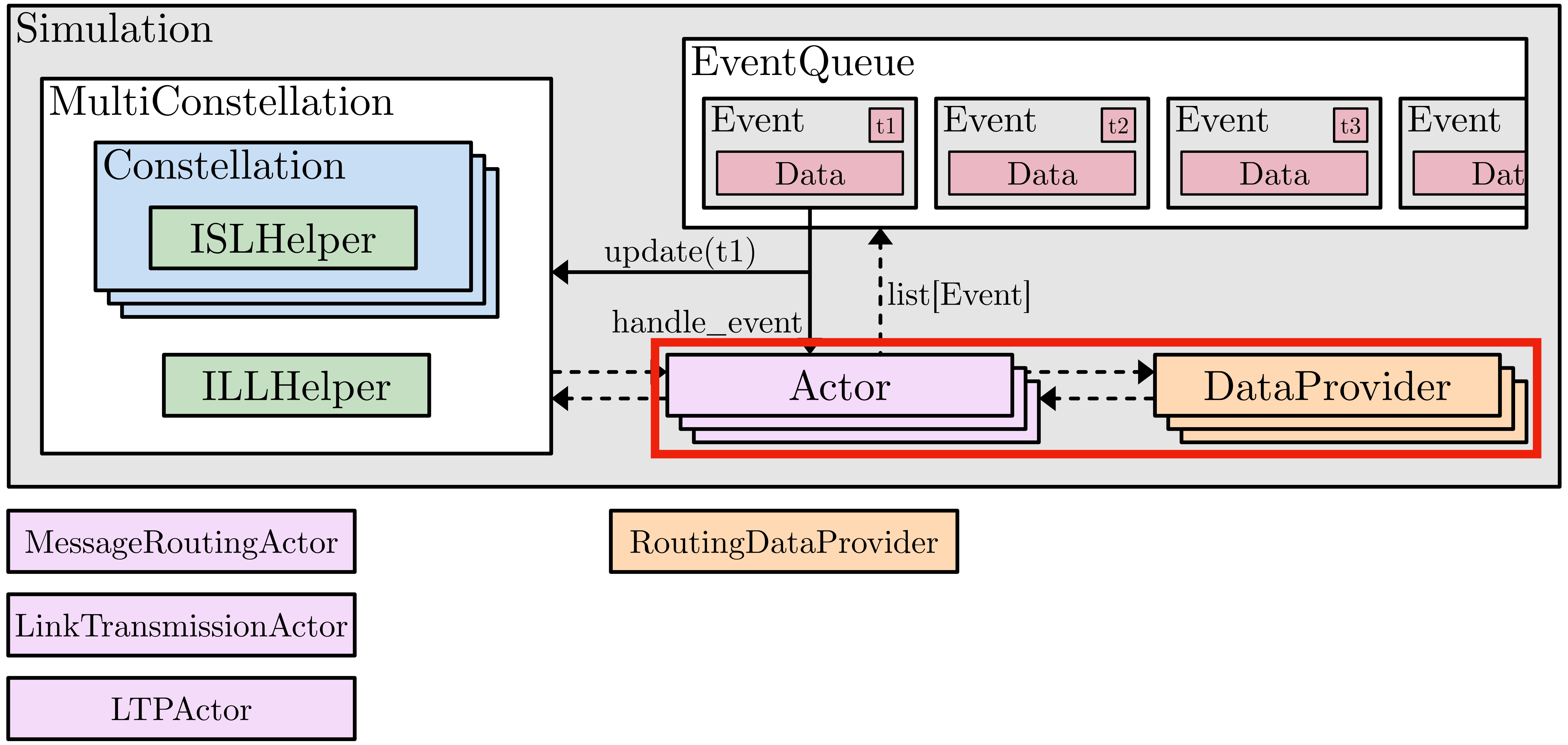

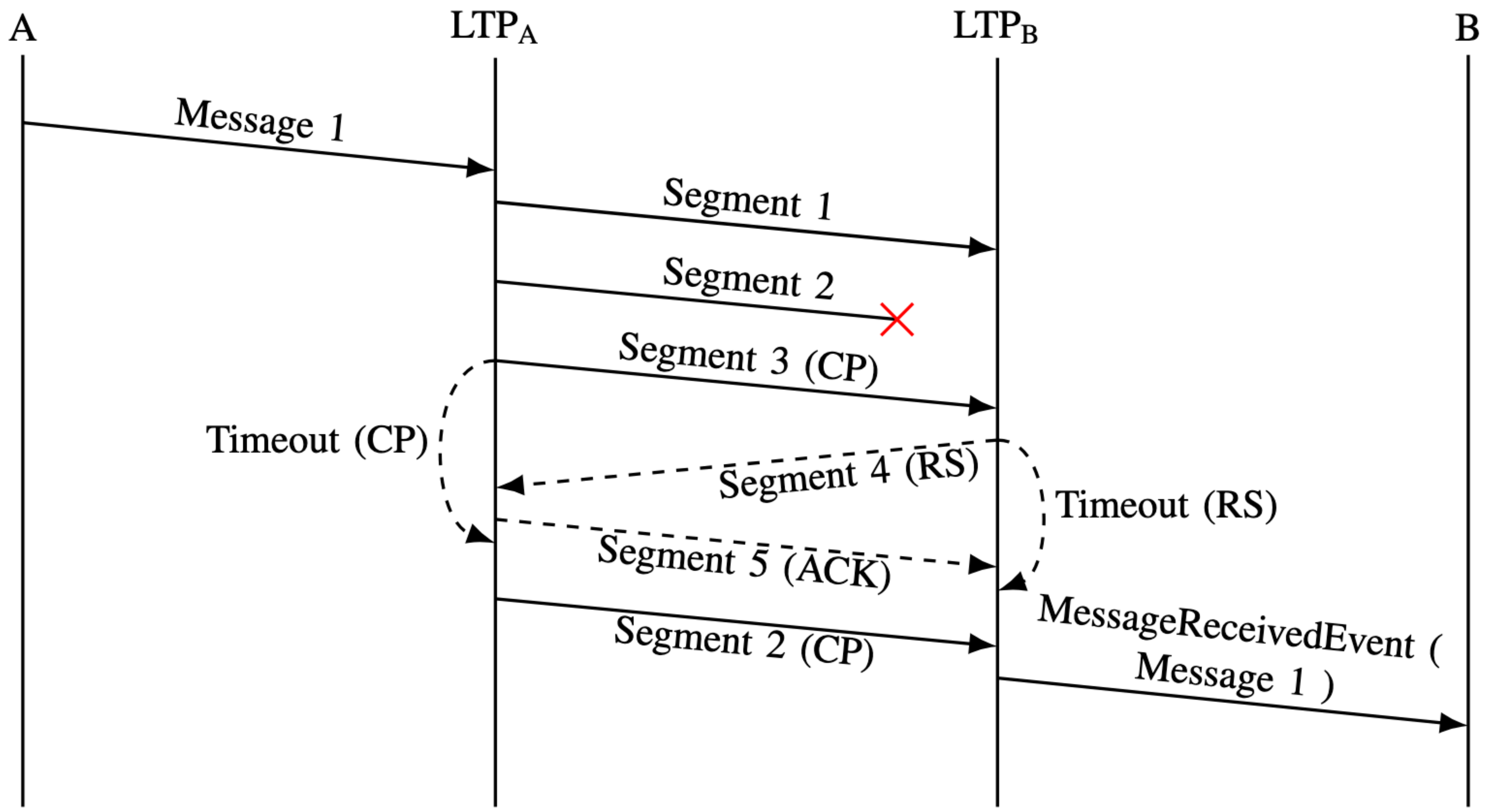

Reference Scenarios

Example configurations to be used as a reference, or a starting point for further development

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CCSDS scenarios:[1]

[1] CCSDS. *Reference Scenarios [DRAFT YELLOW BOOK]*. 2023.

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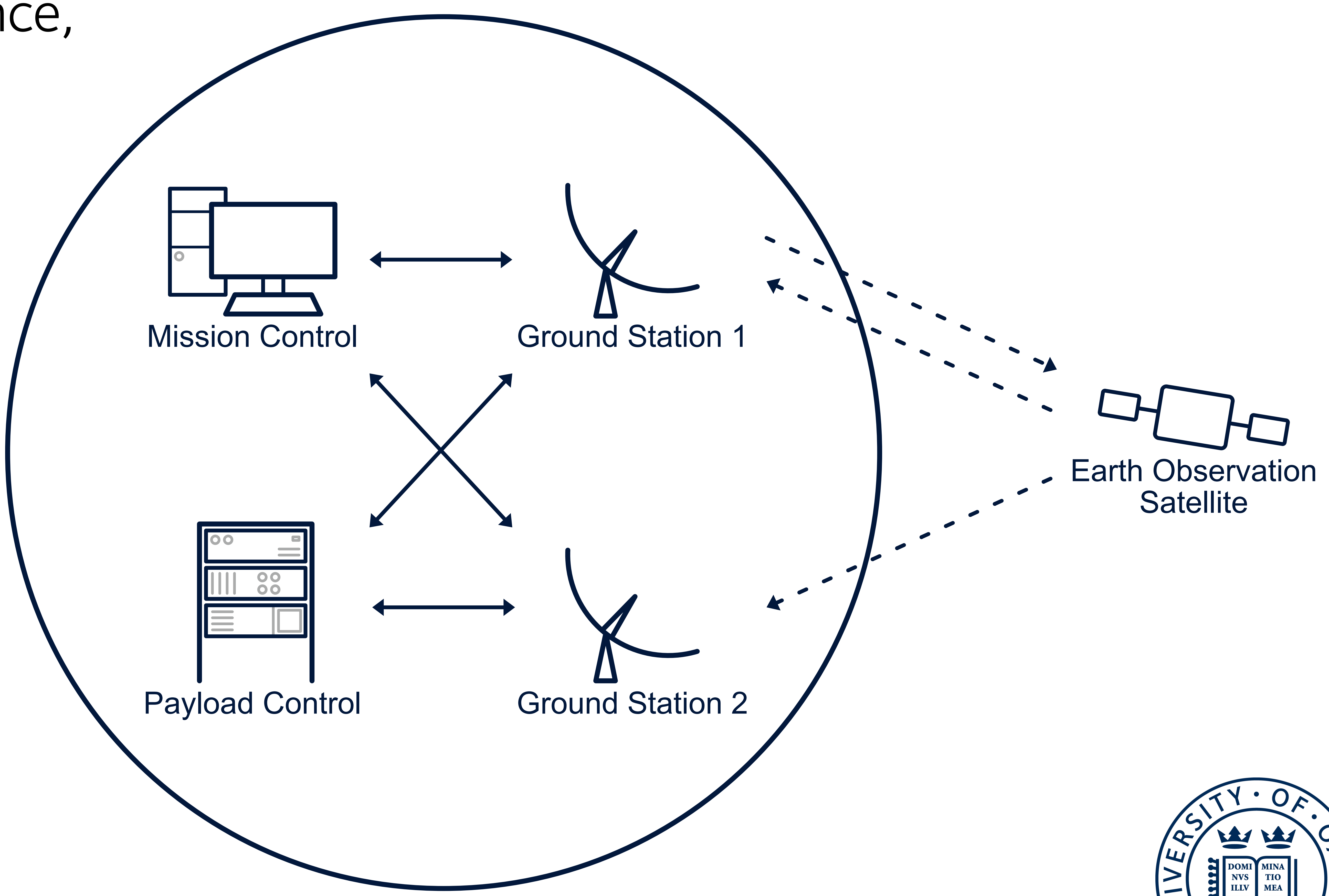
CCSDS scenarios:[1]

- Earth observation



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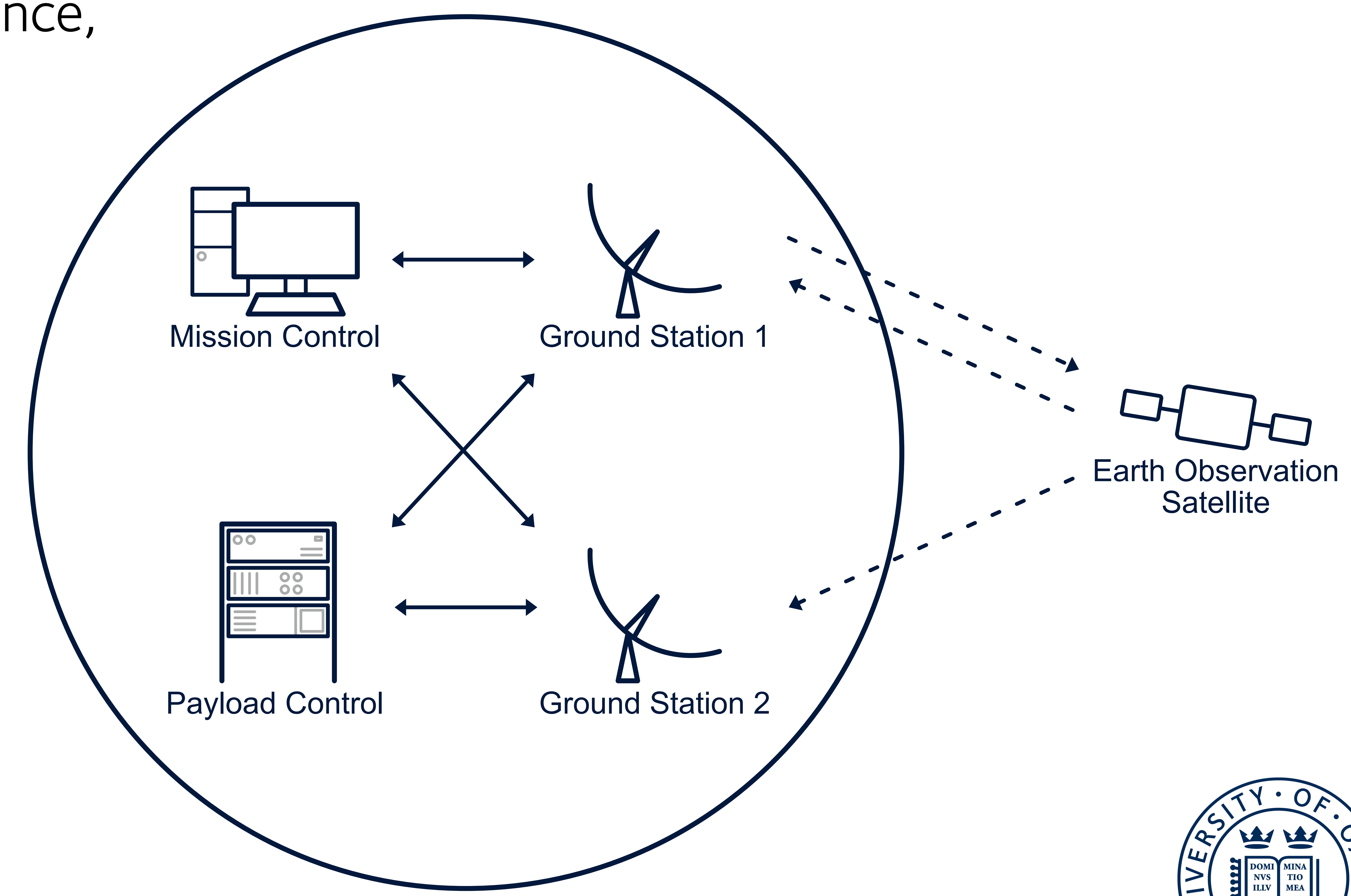

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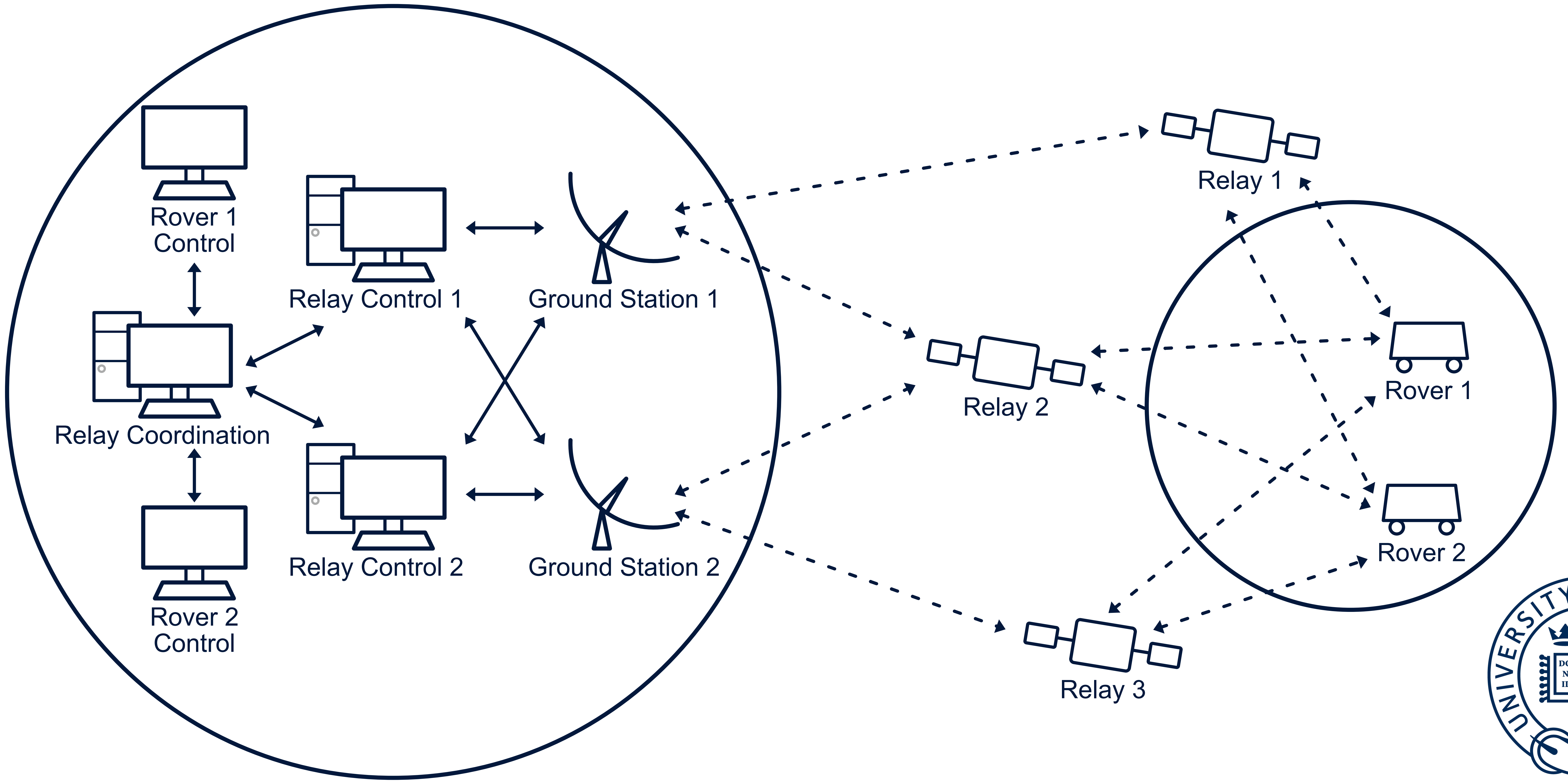

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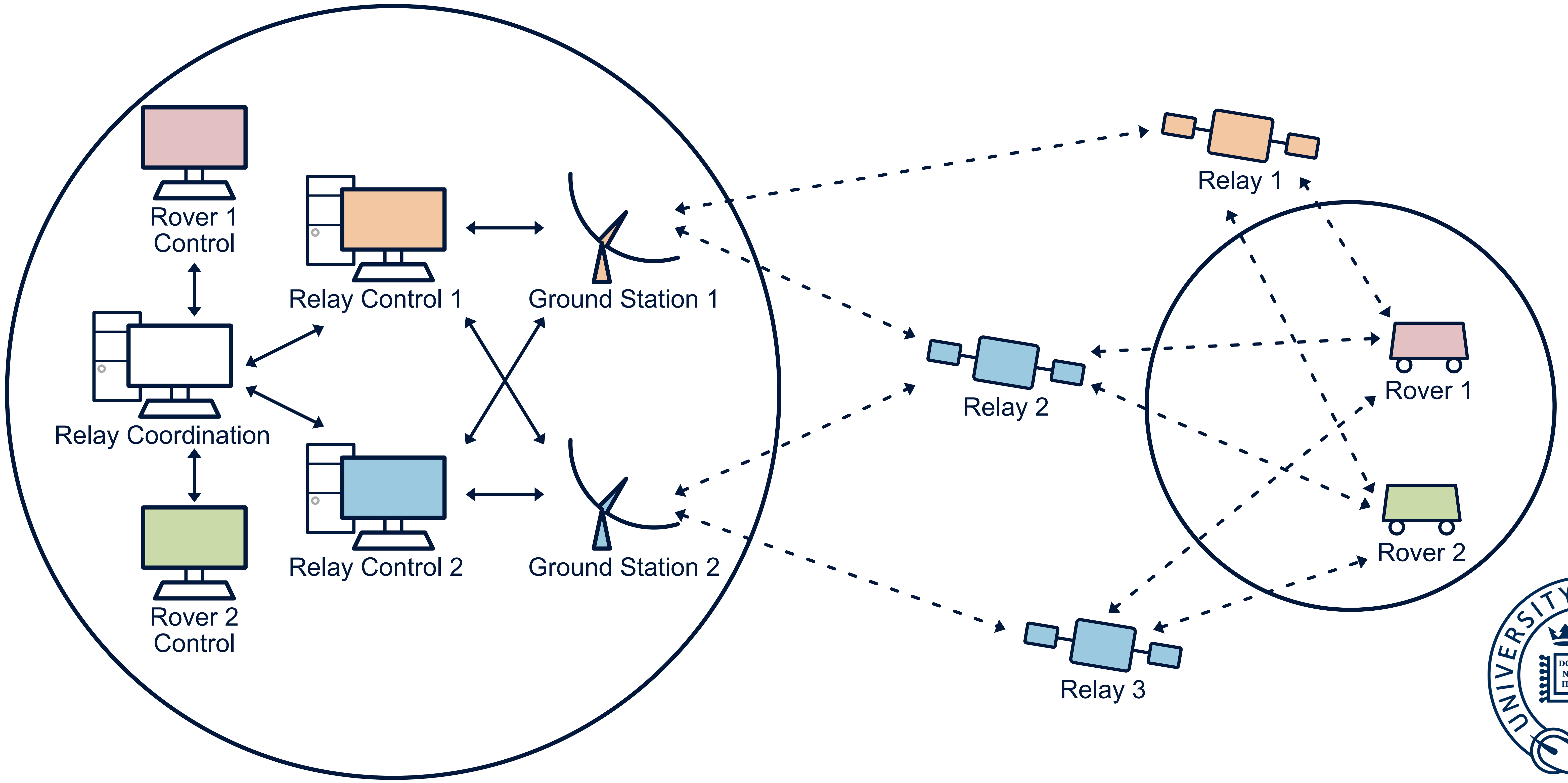

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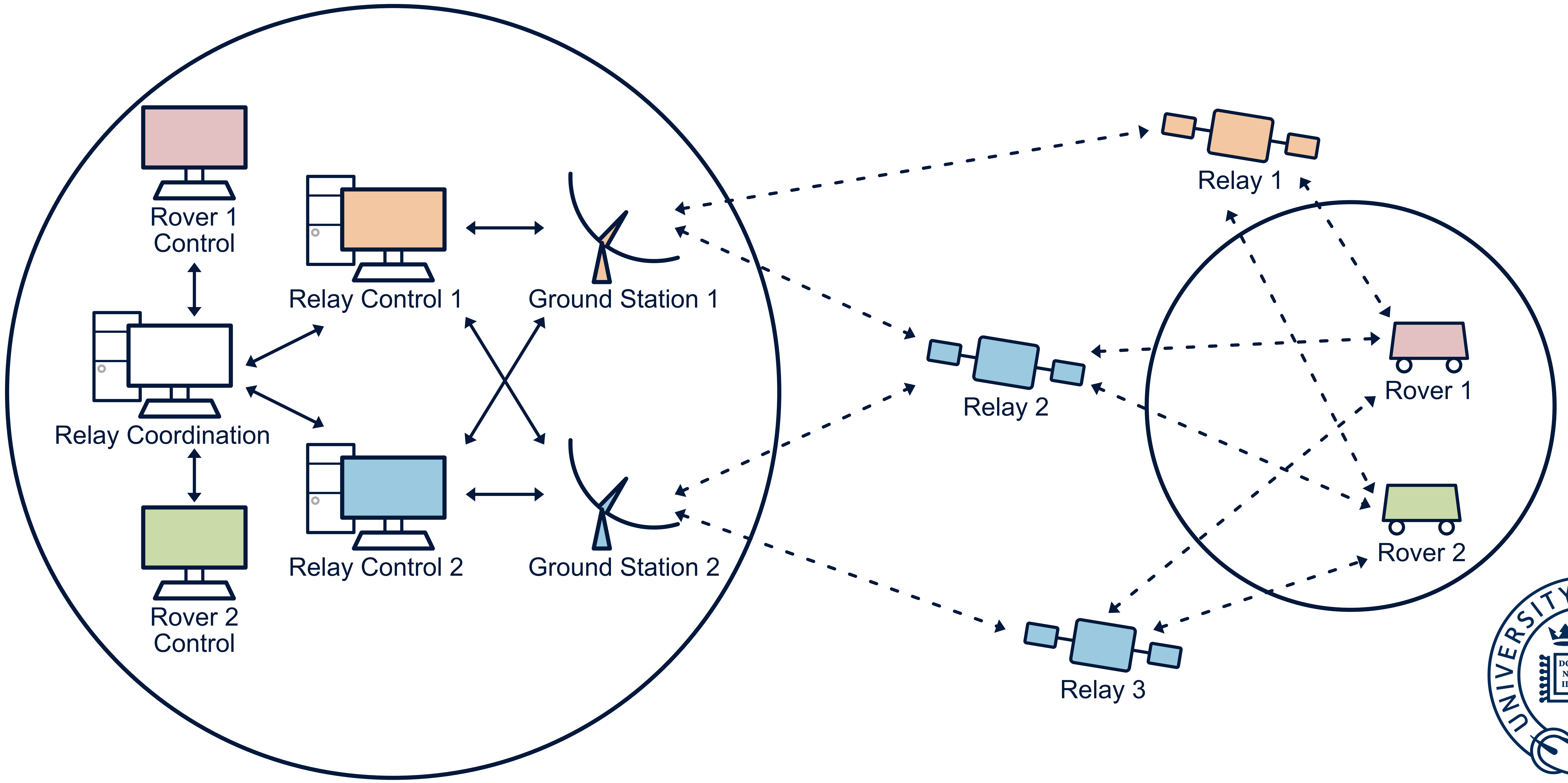

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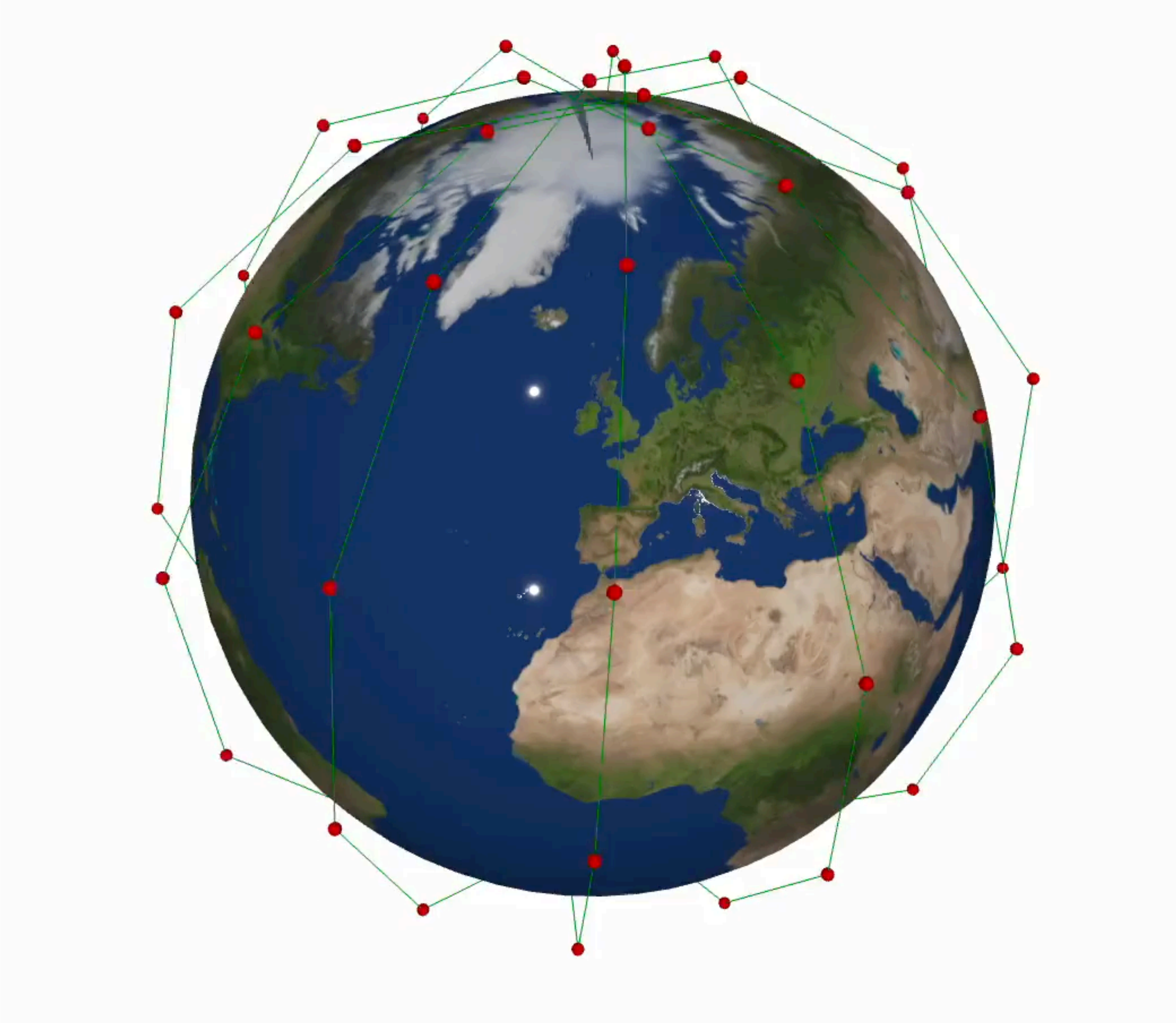

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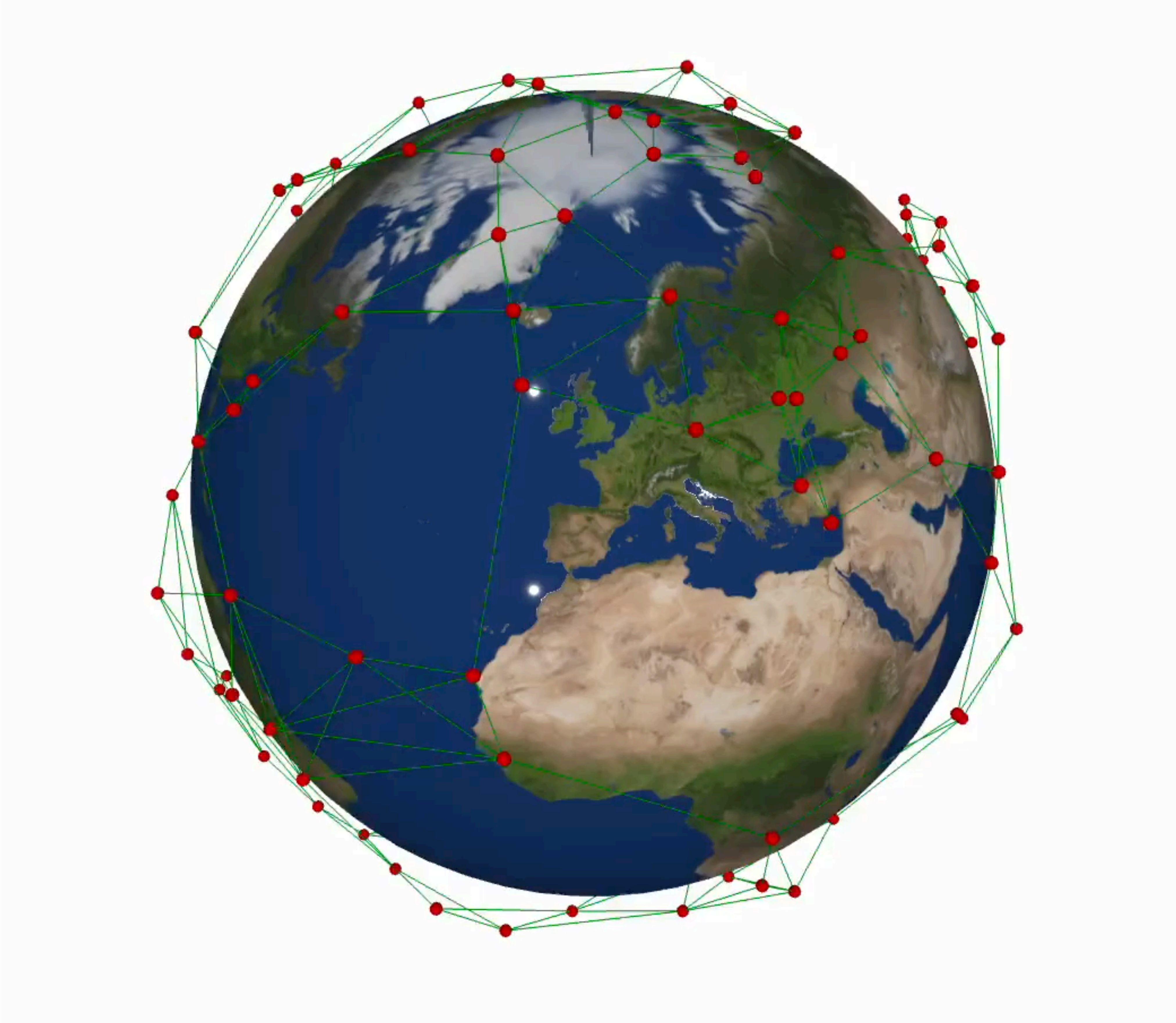

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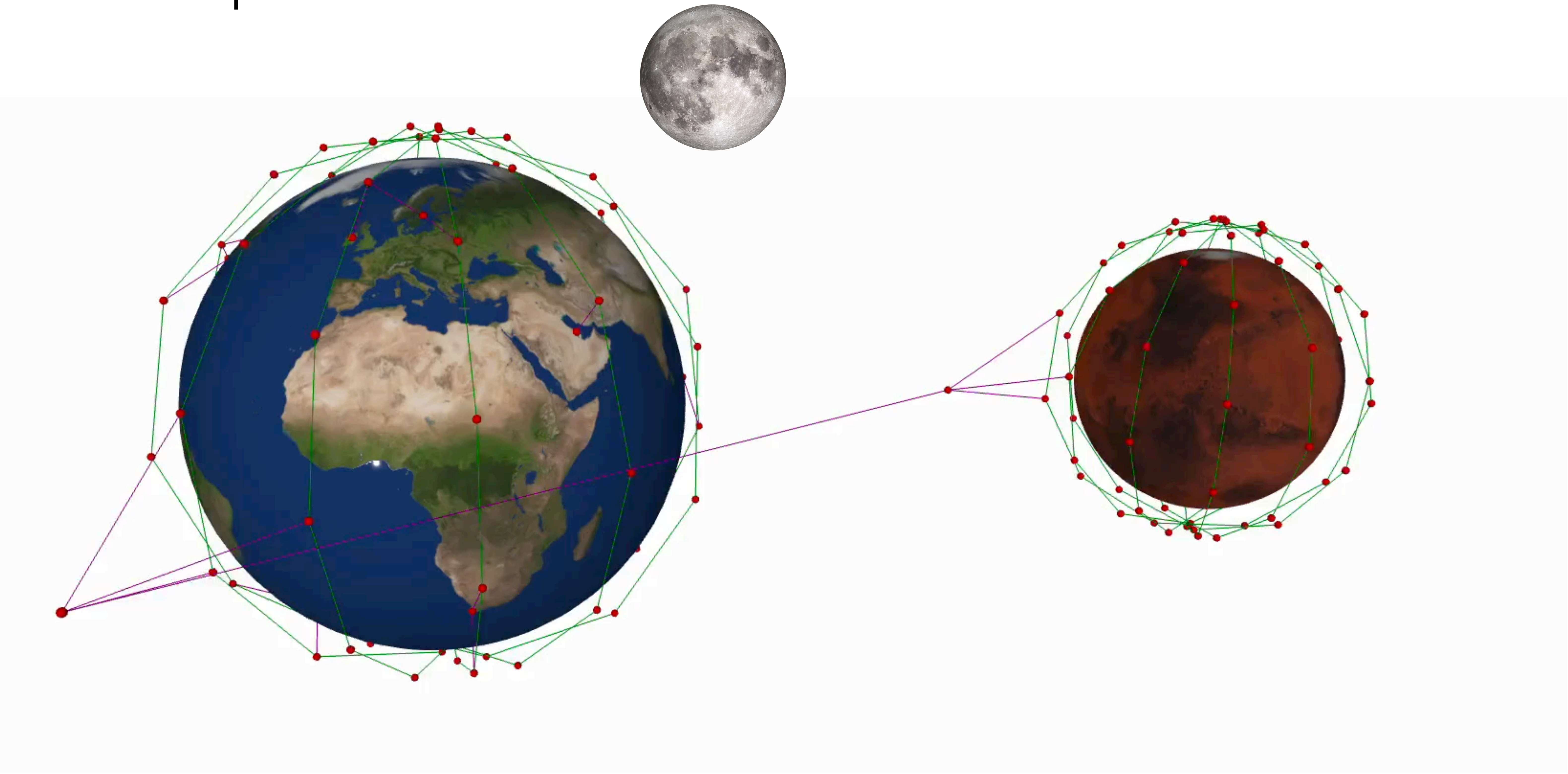

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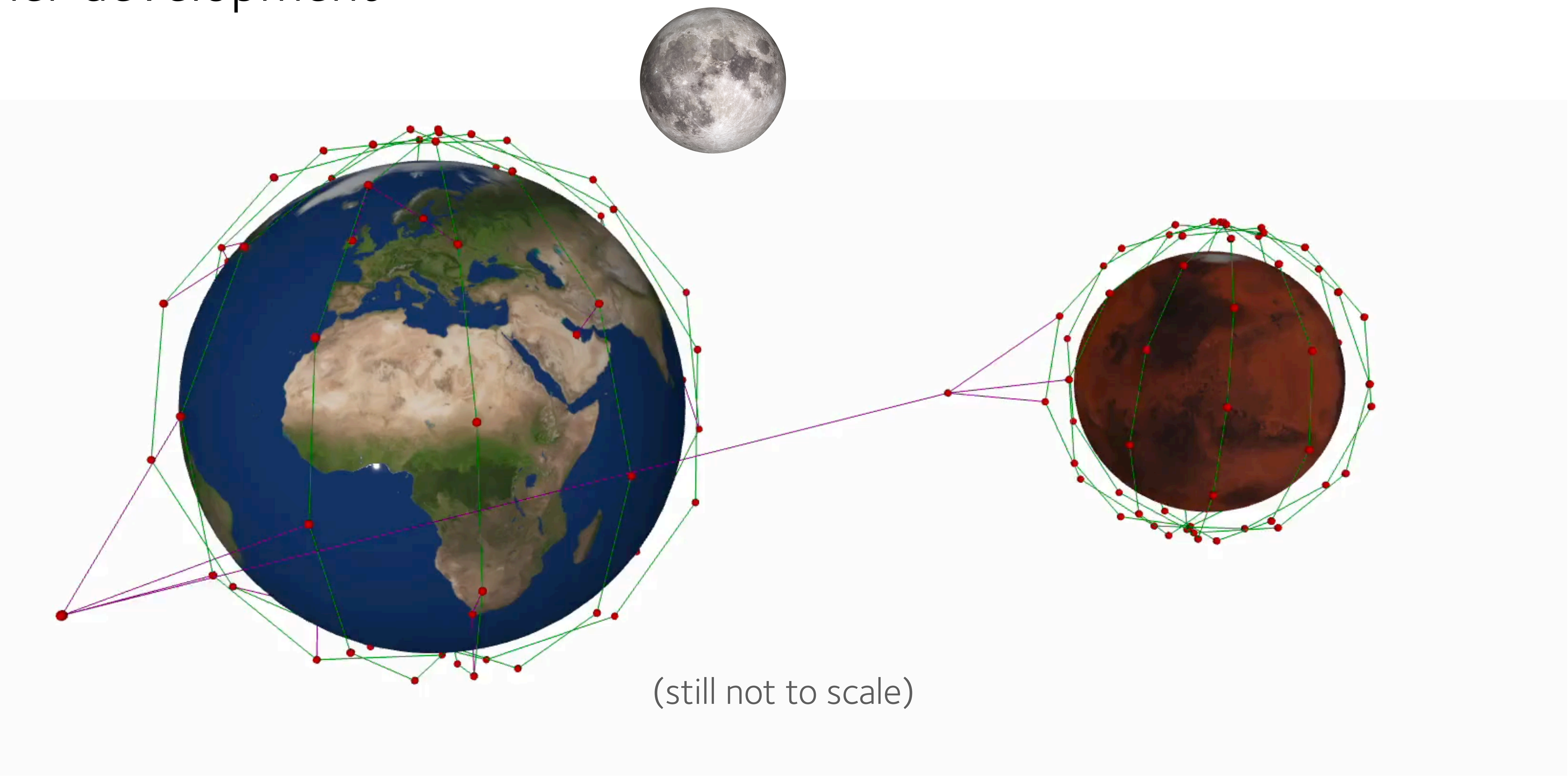

(still not to scale)

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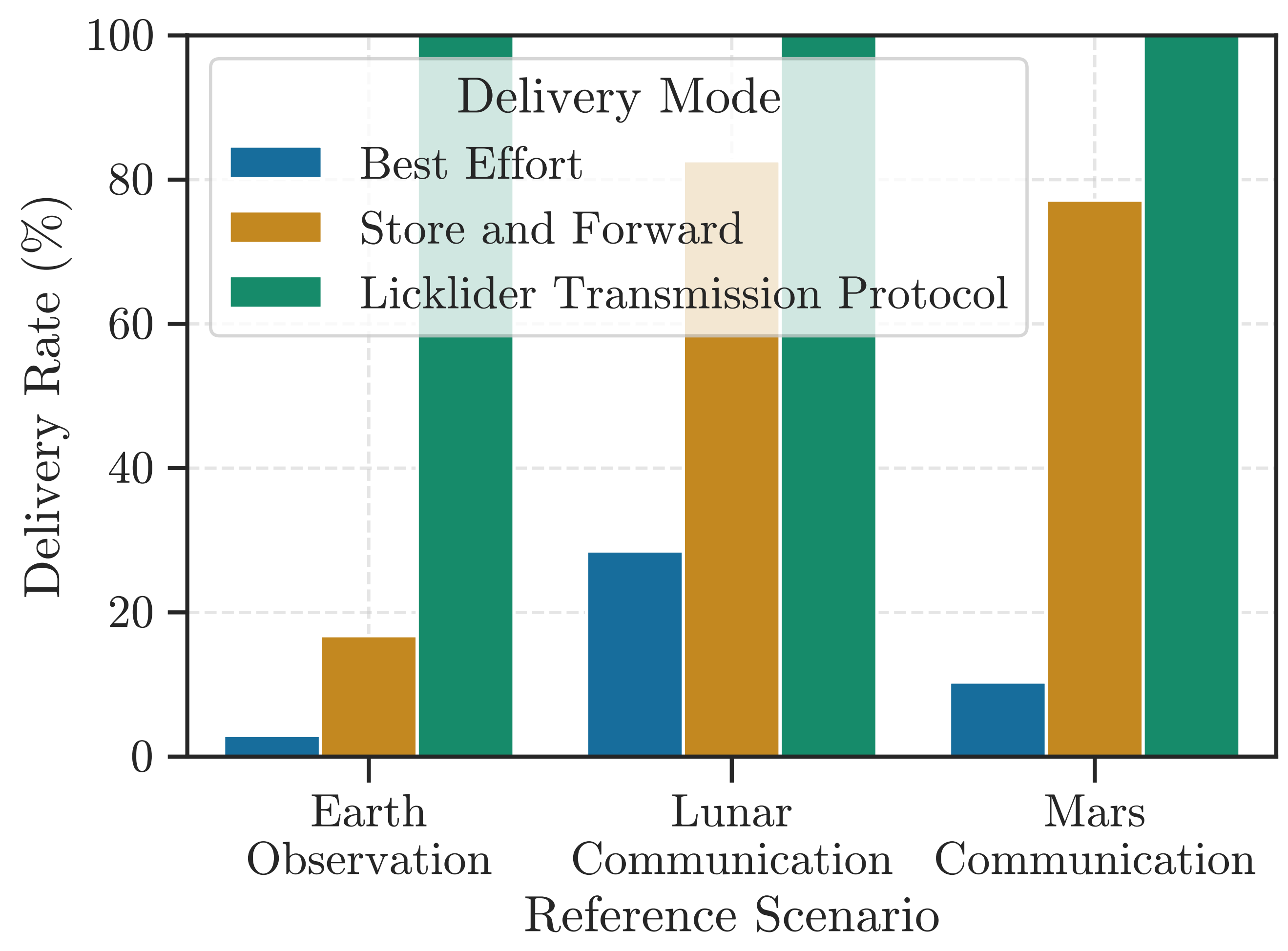
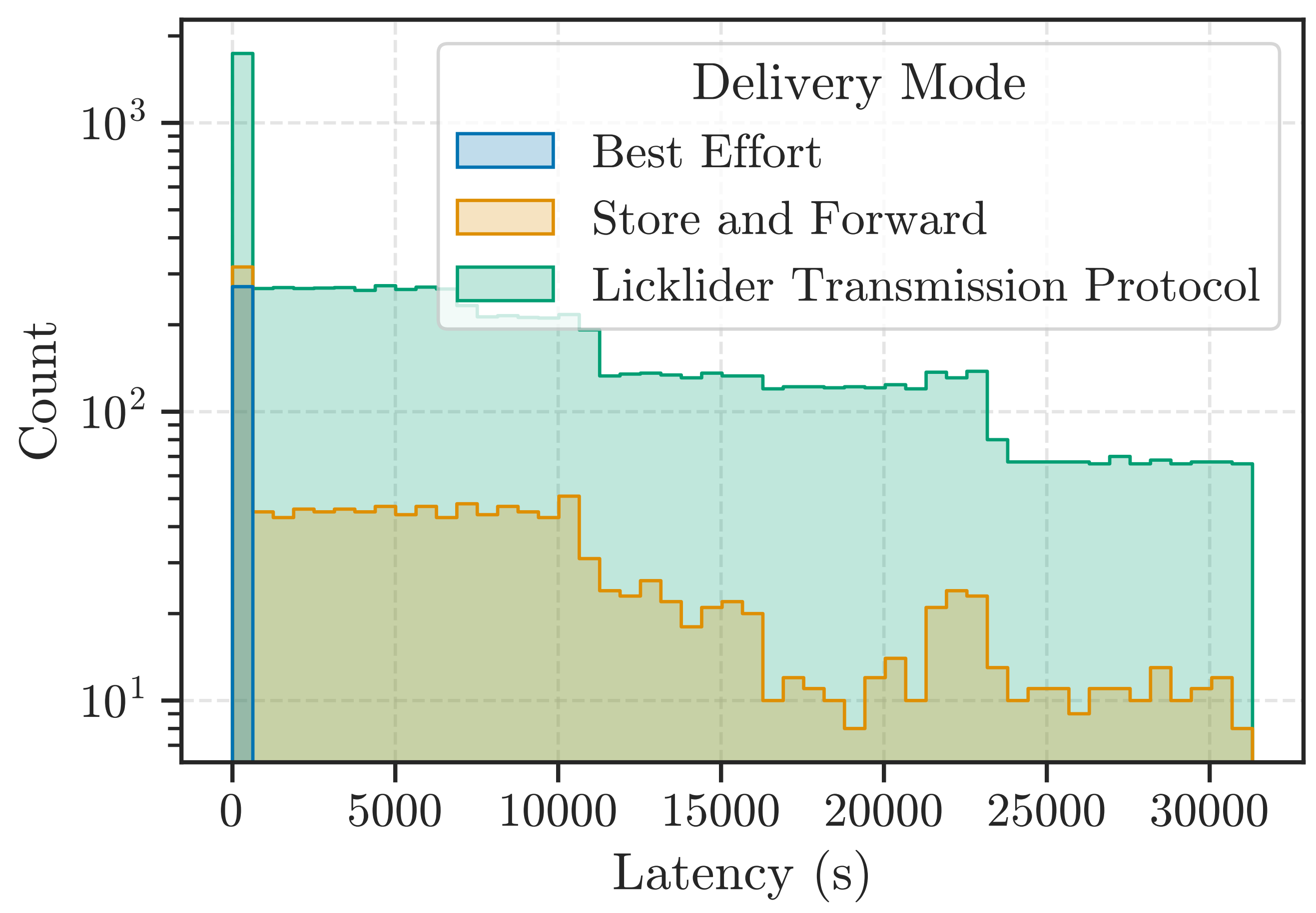
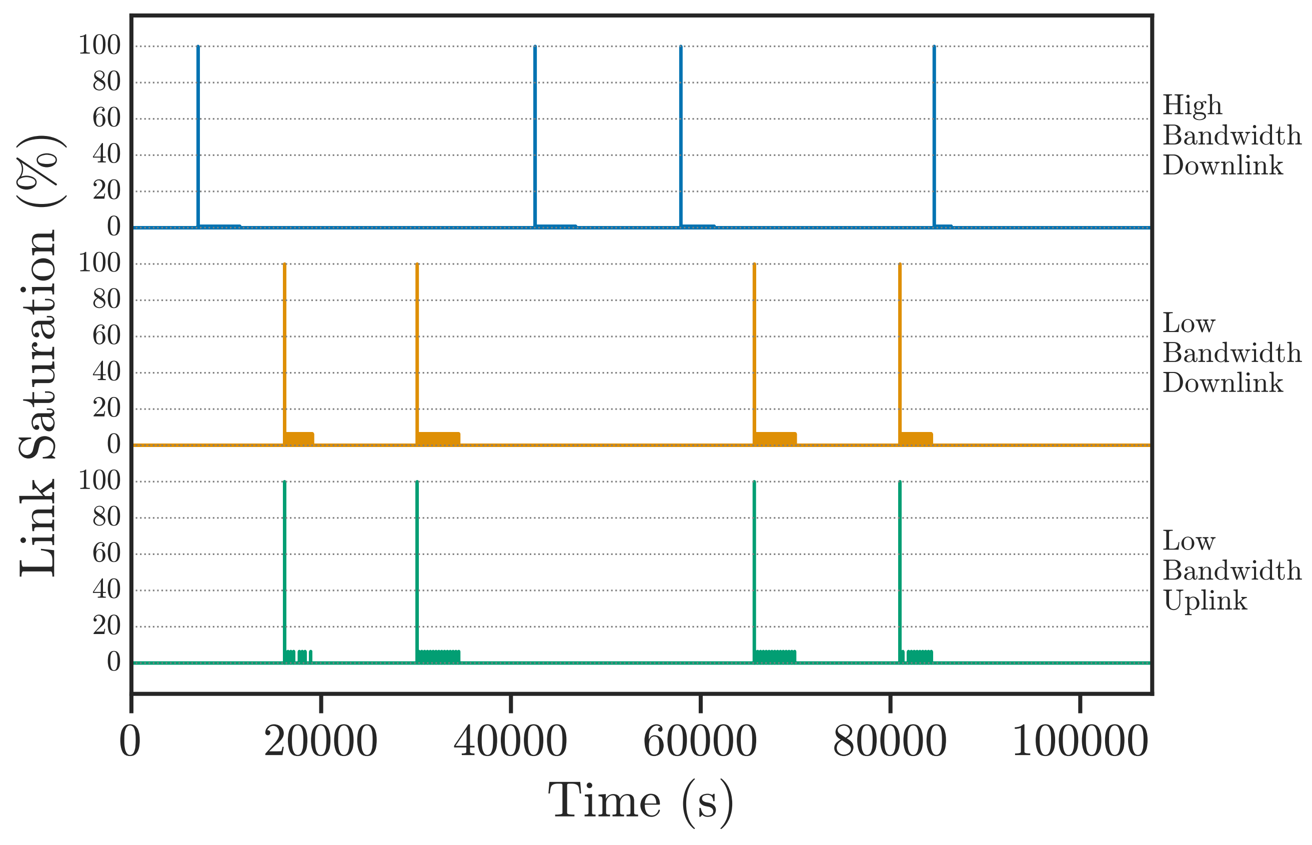
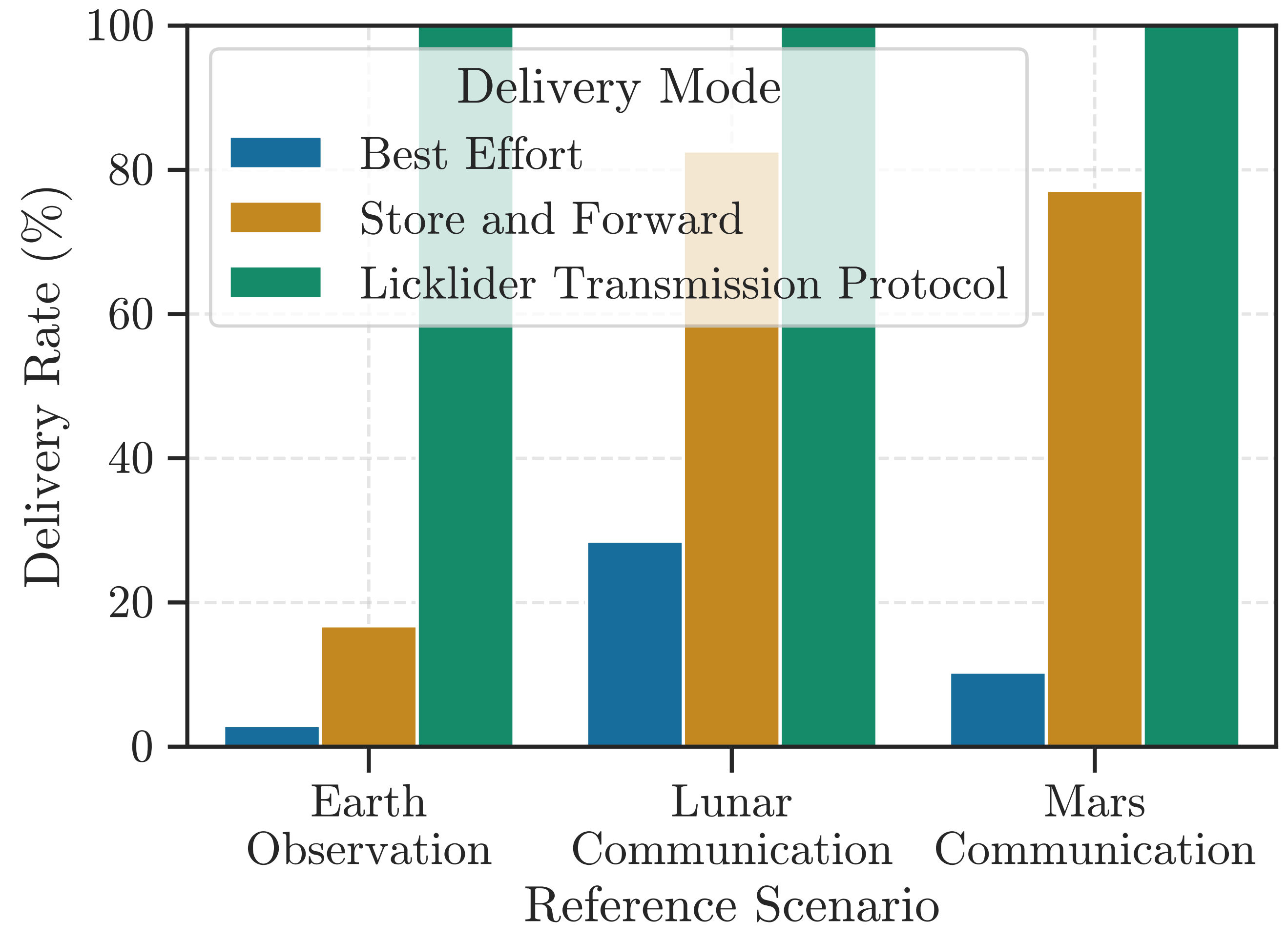


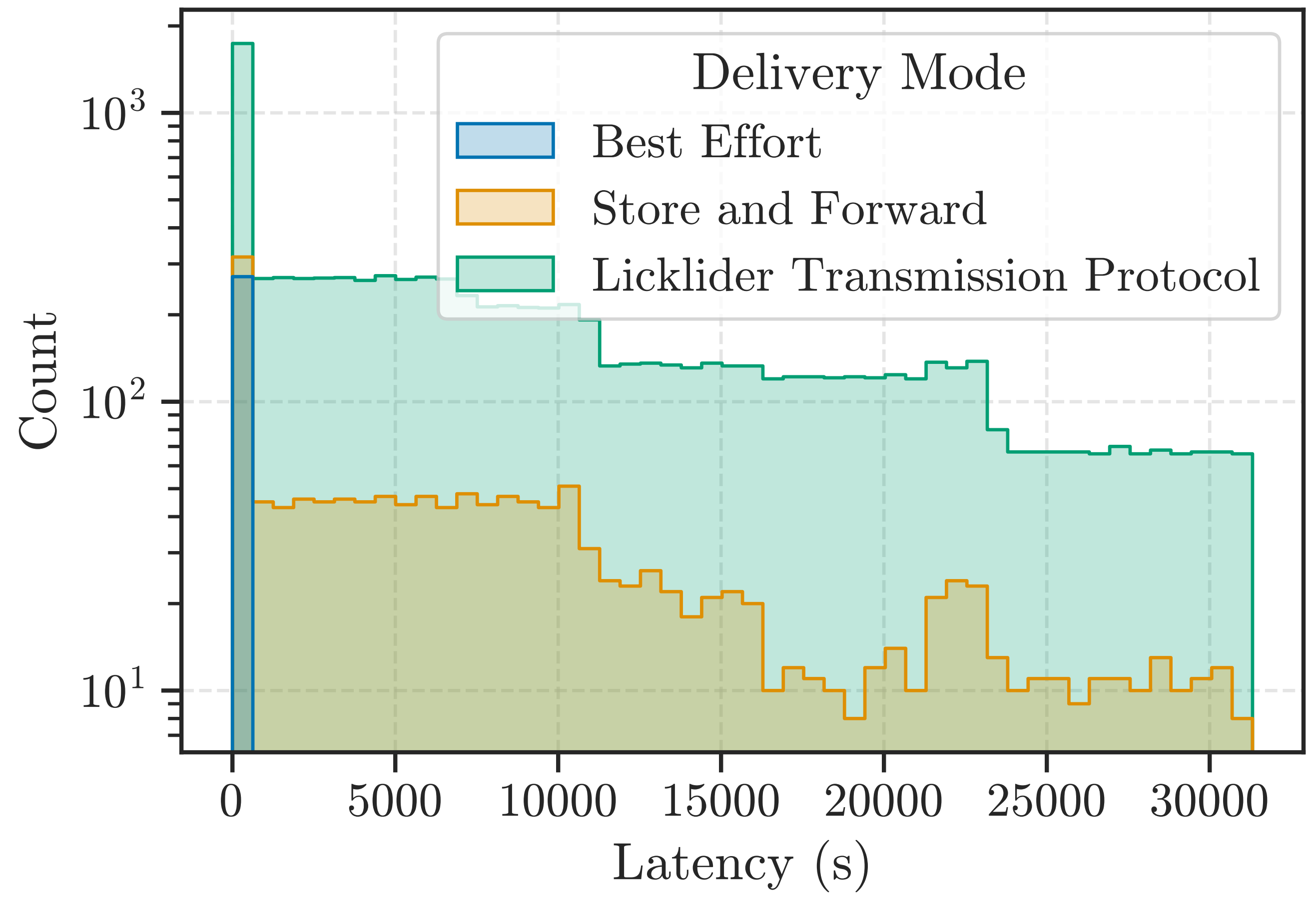


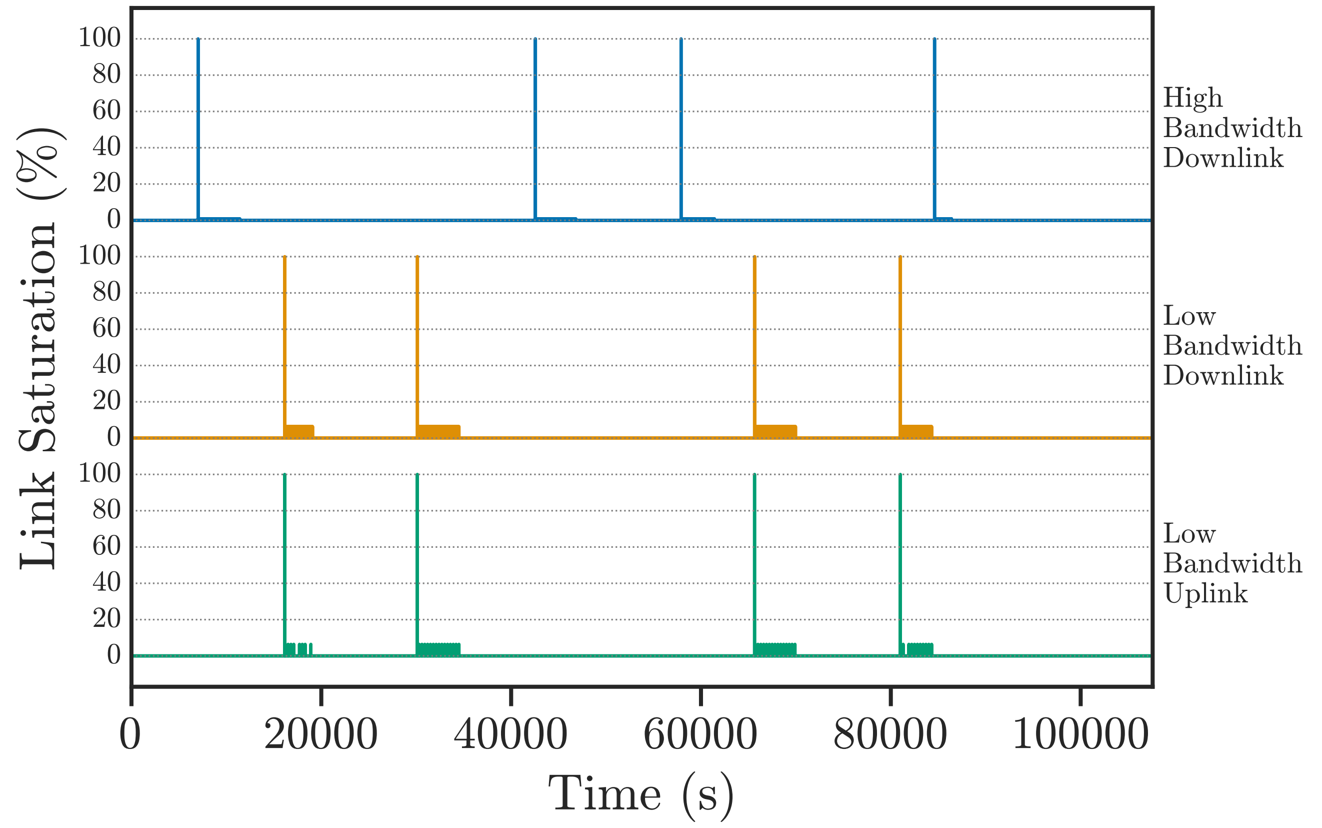


- DTN reference scenarios

Results







- DTN reference scenarios
  - Bursts of traffic when links become available to satisfy buildup of traffic

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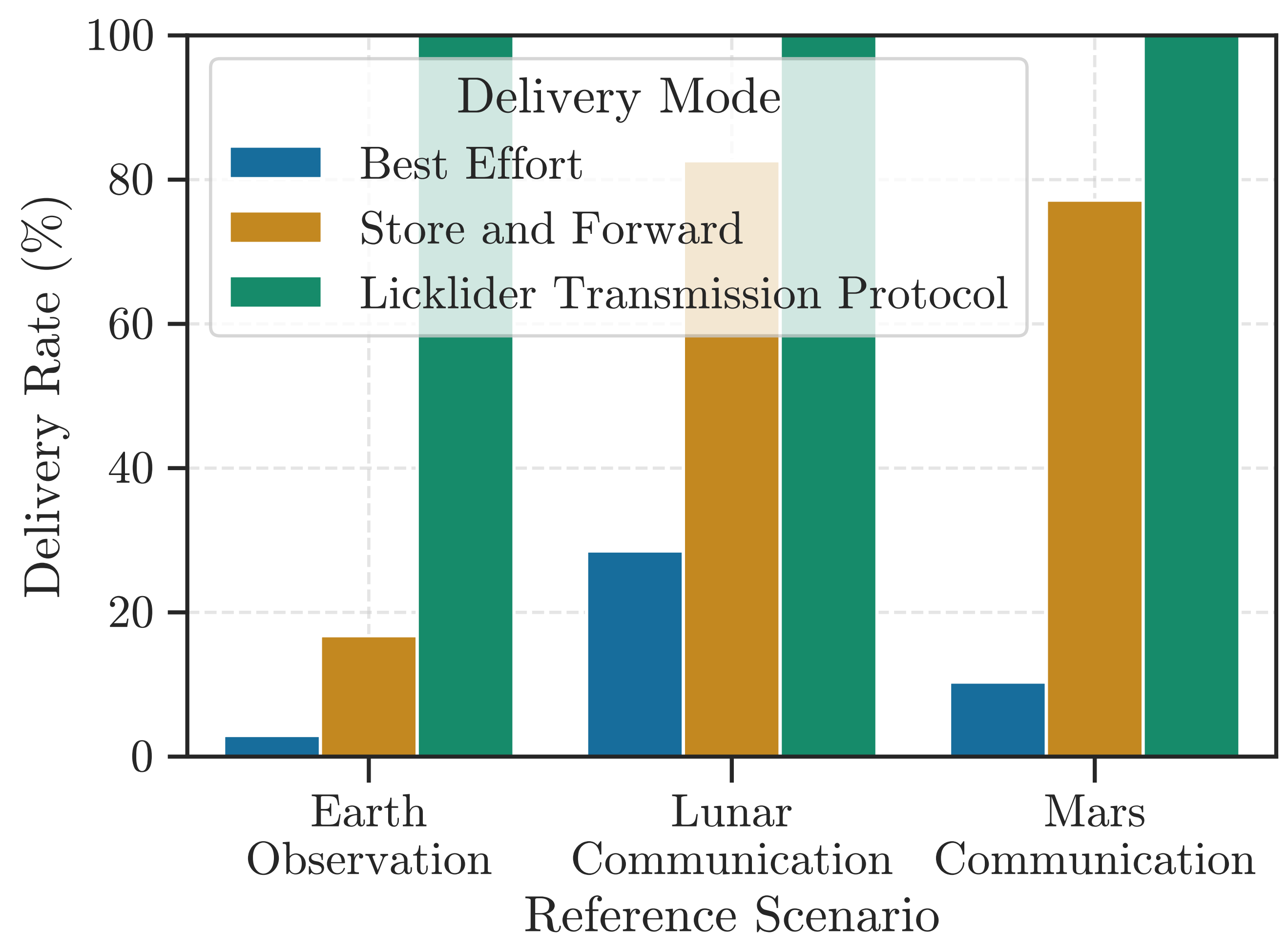

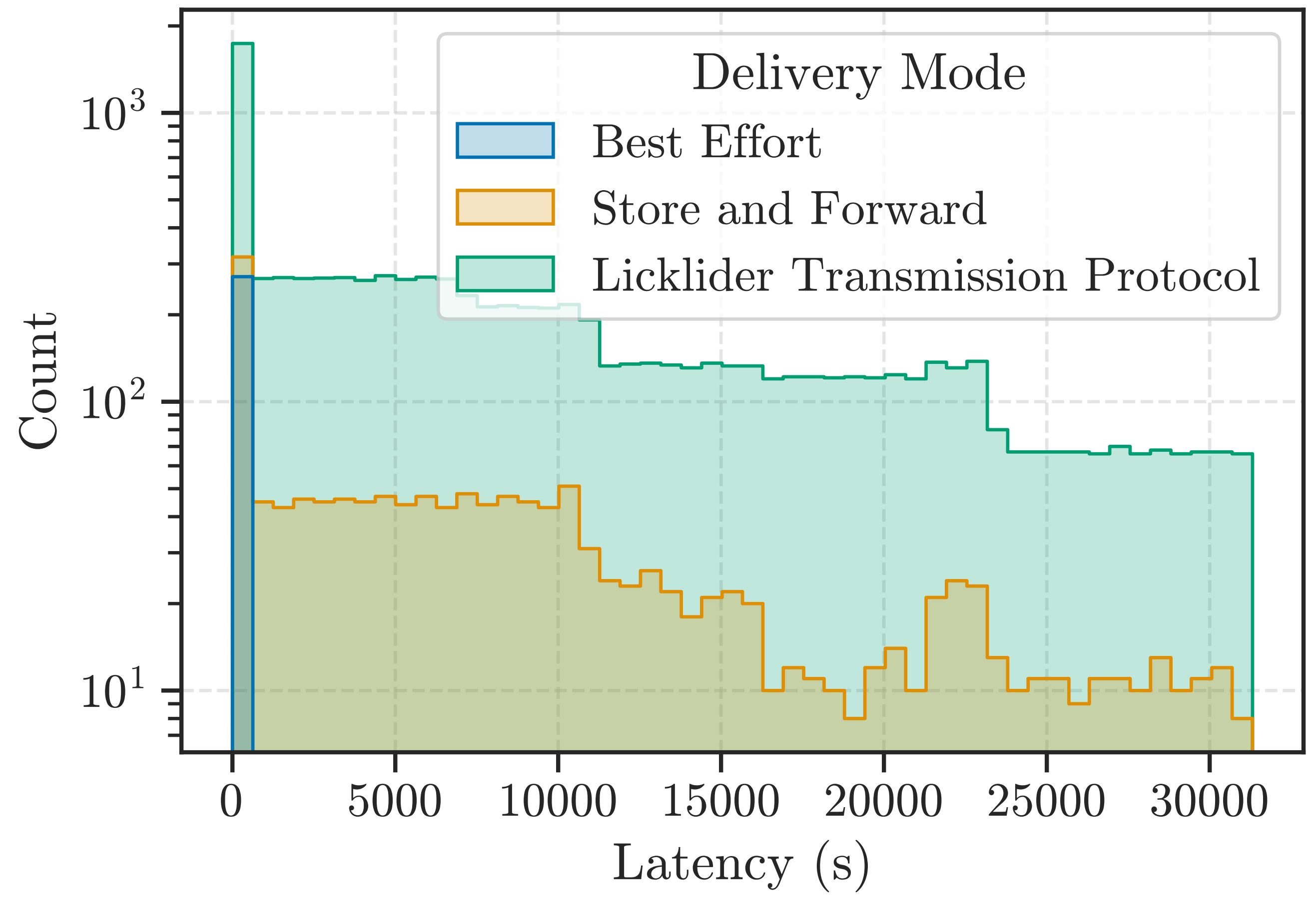

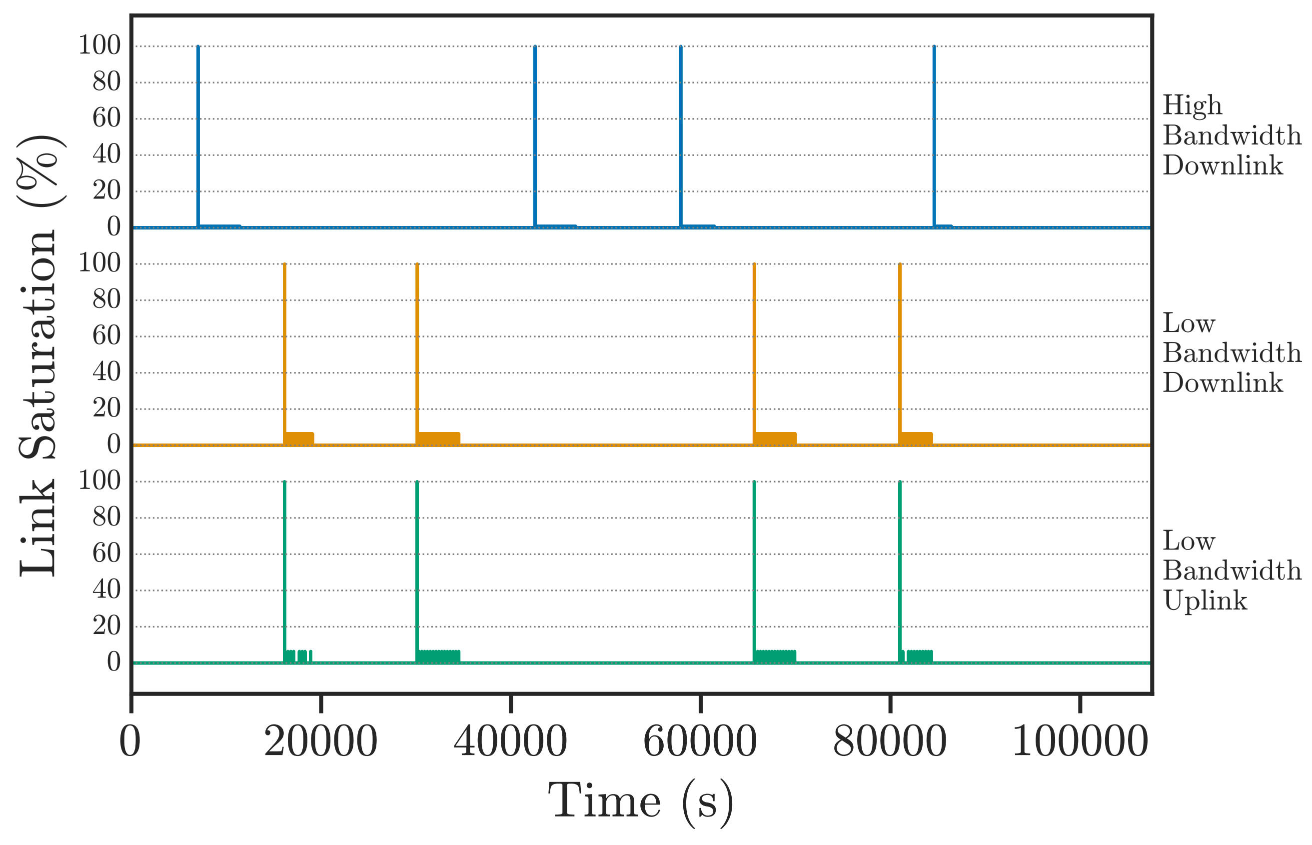

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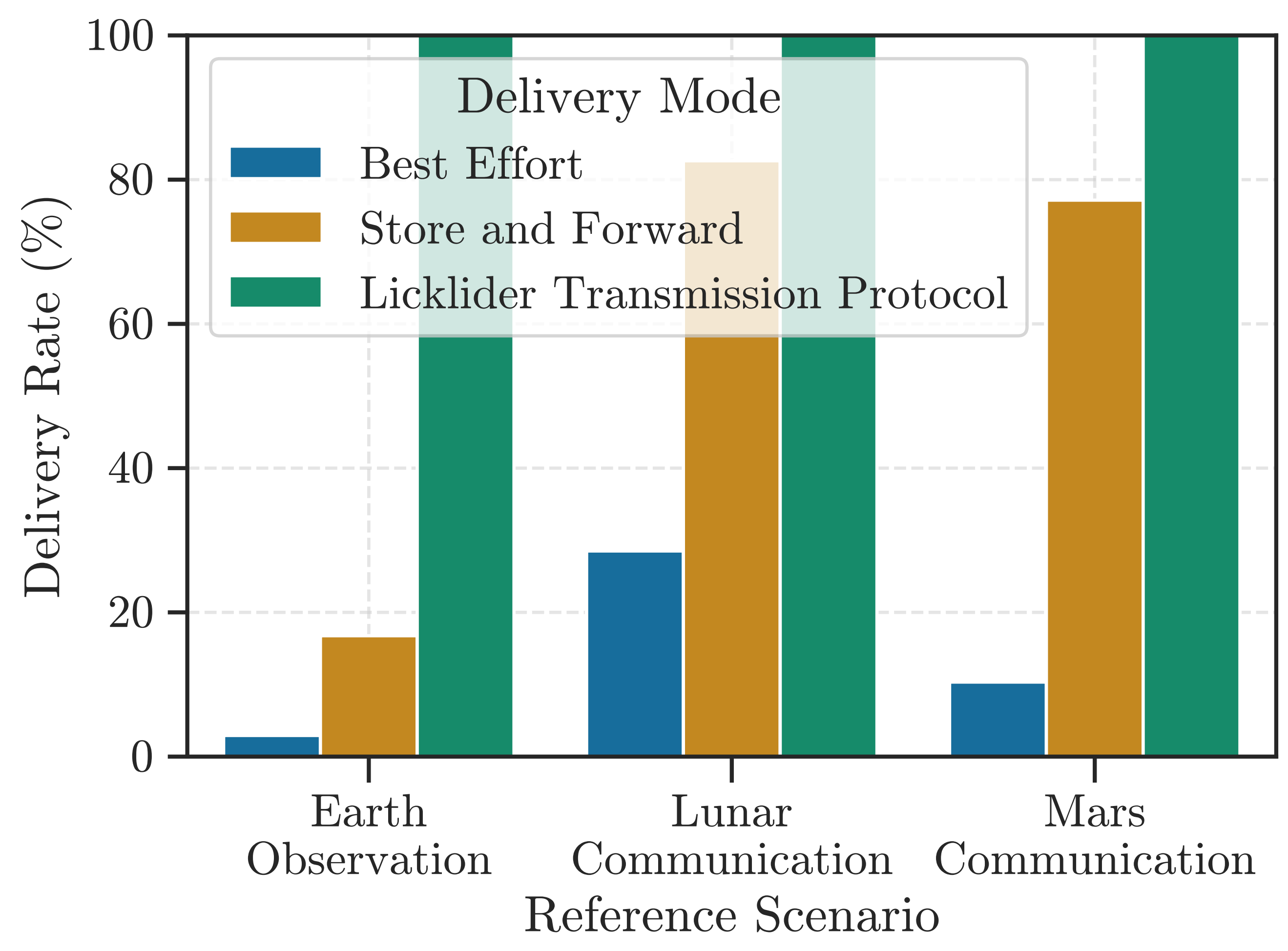
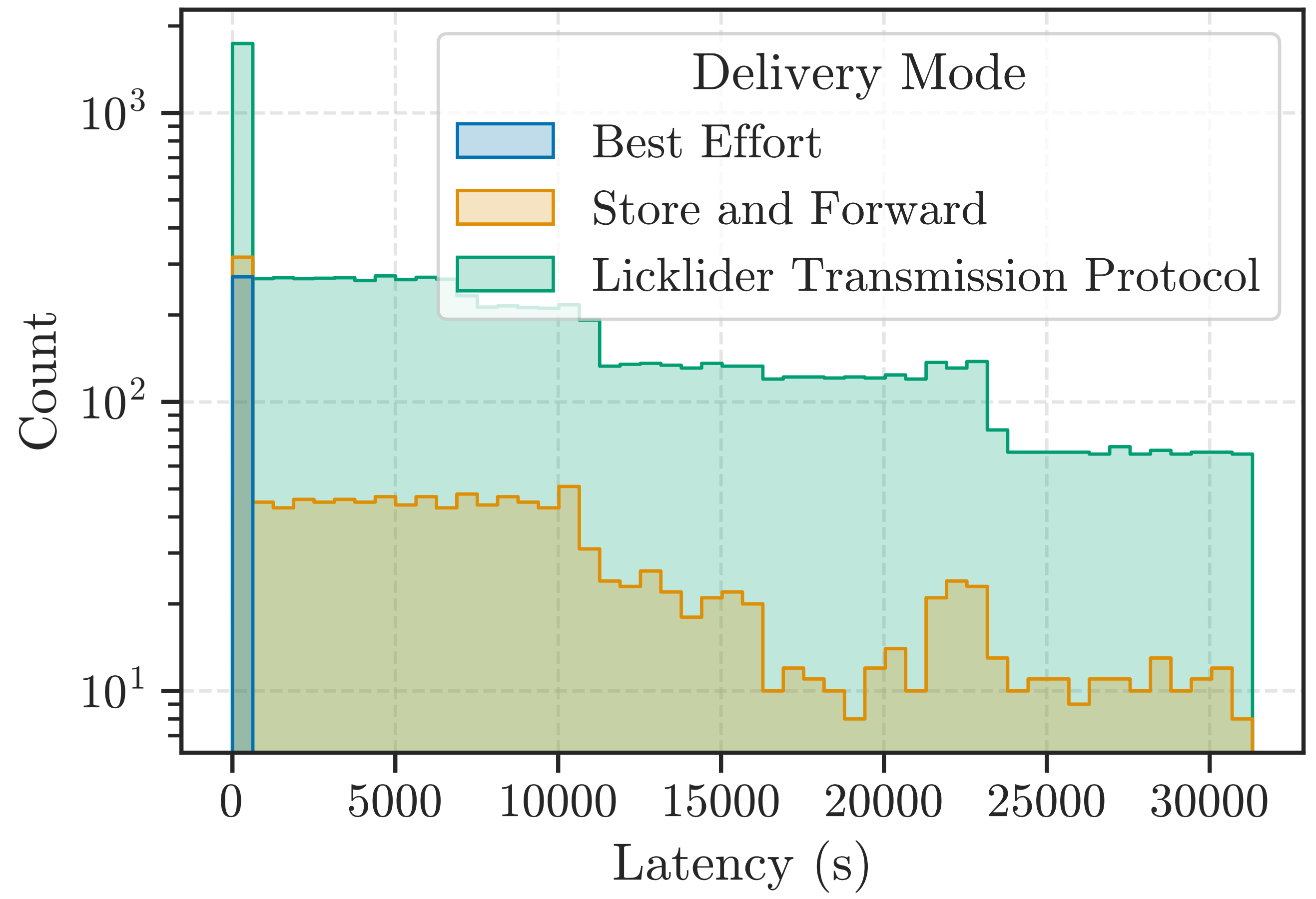
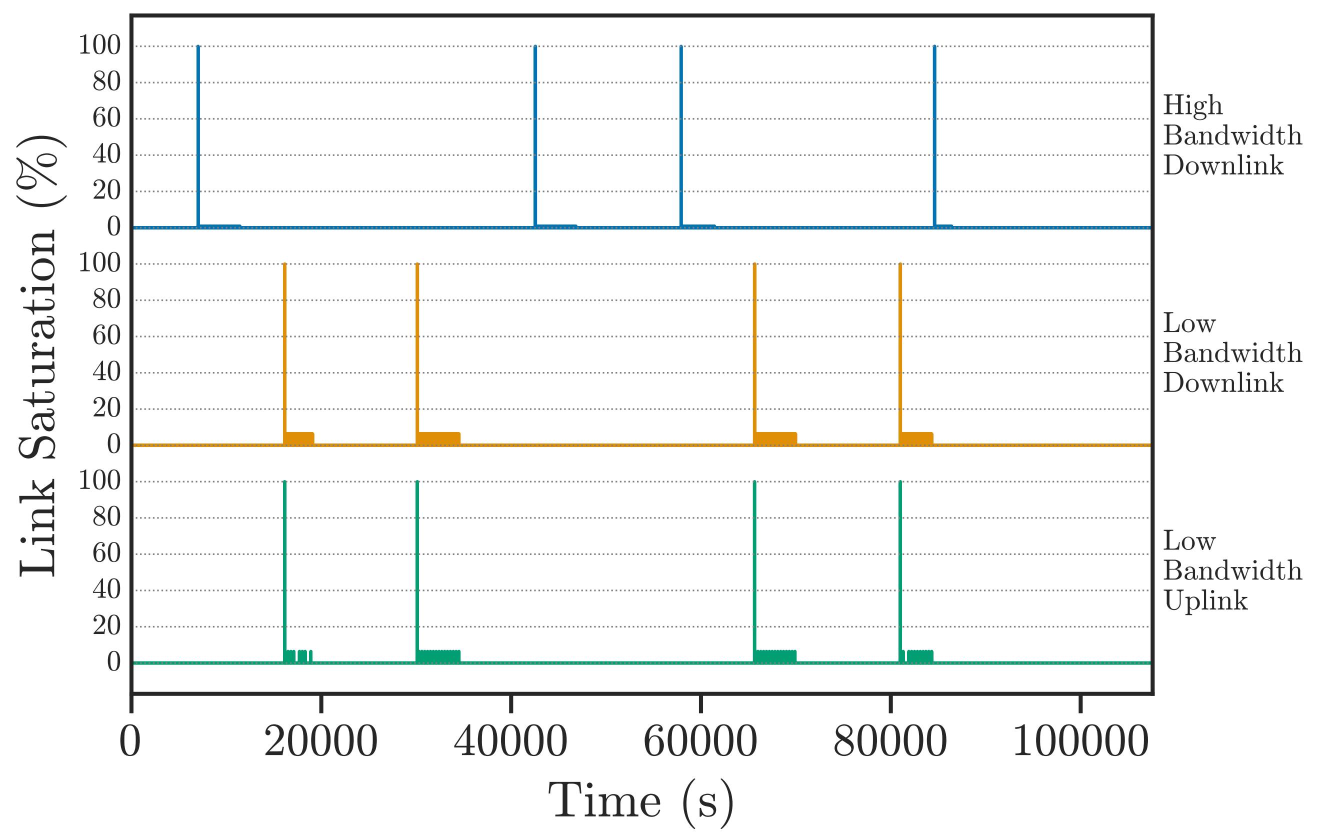
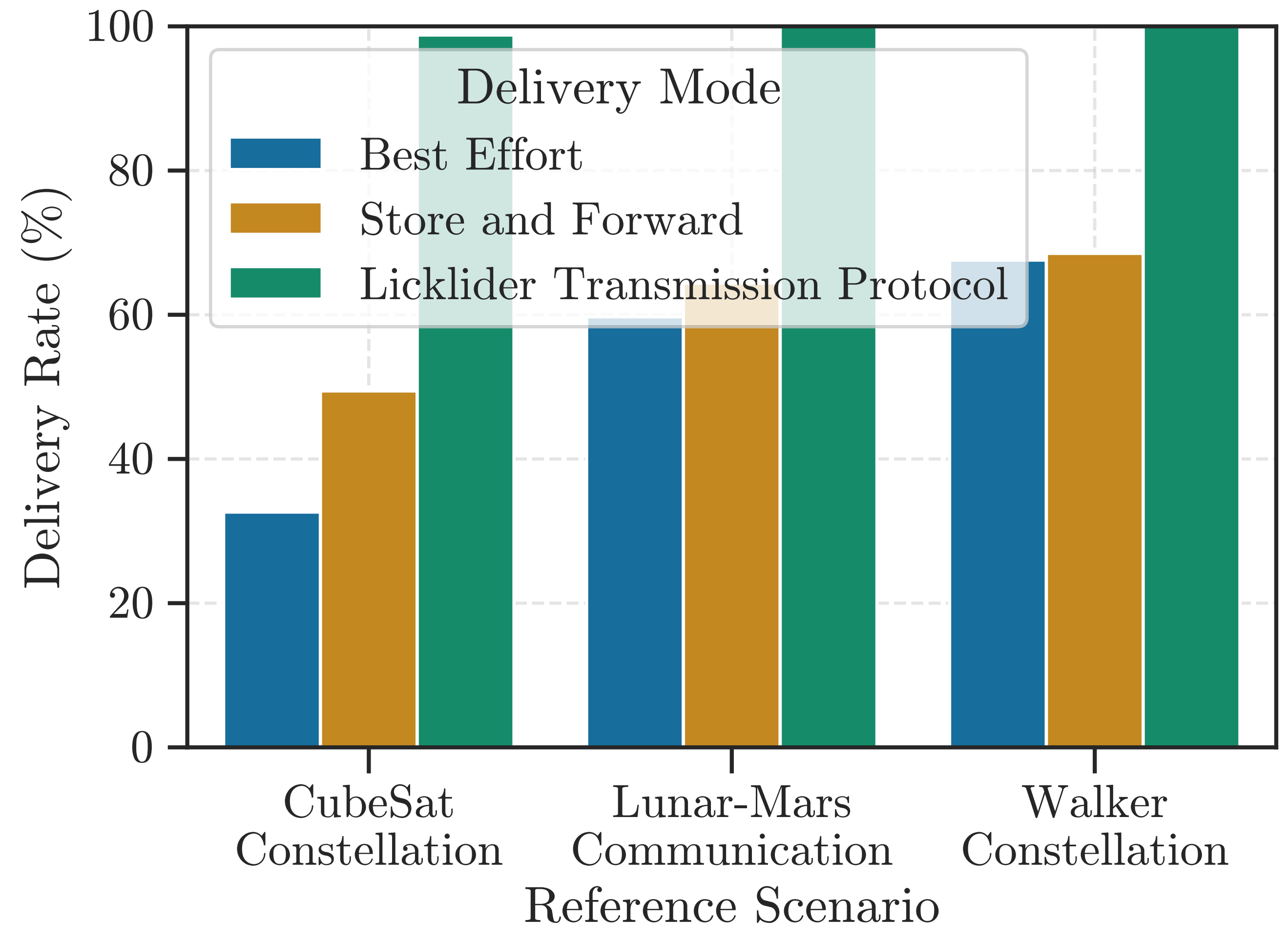


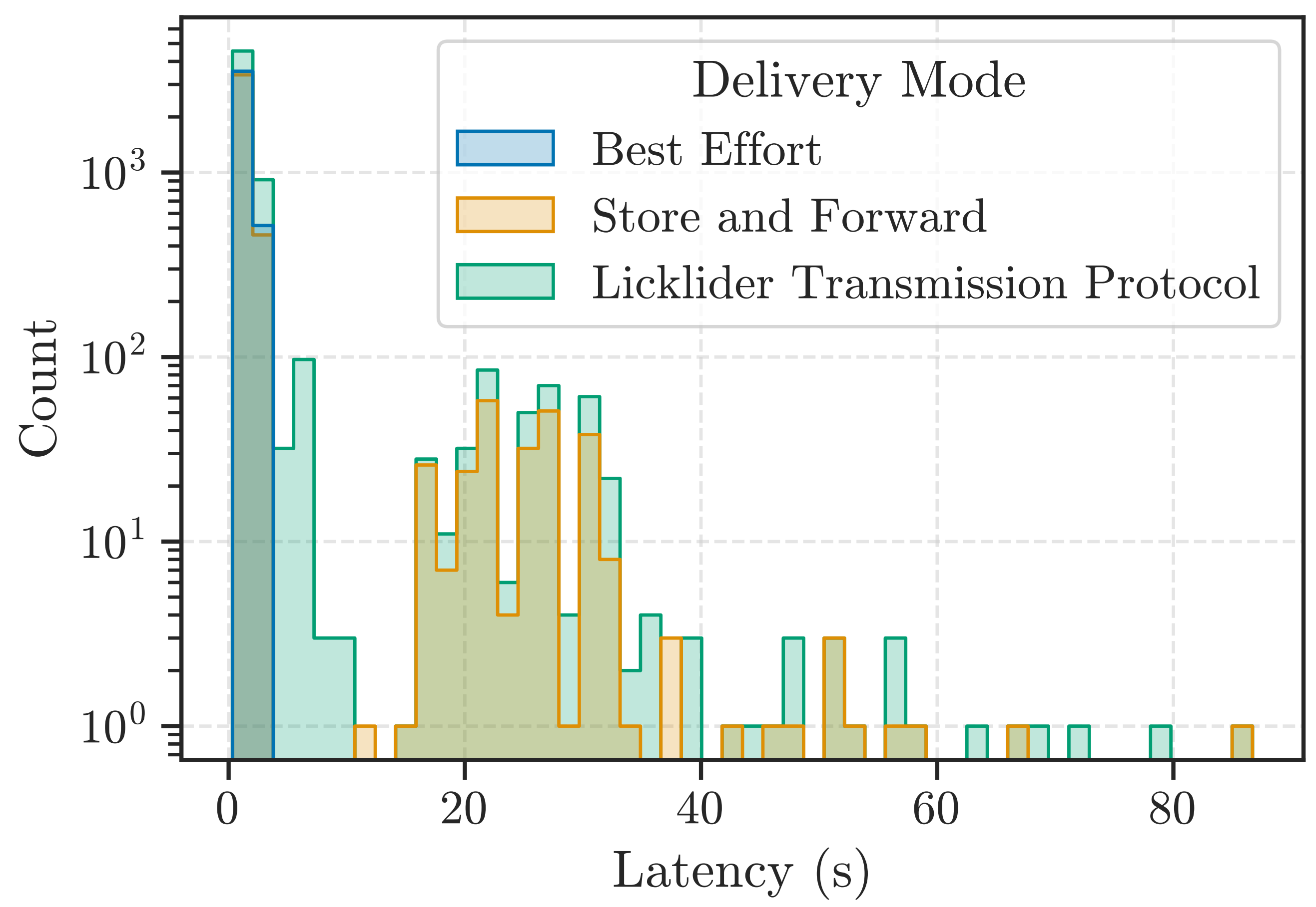


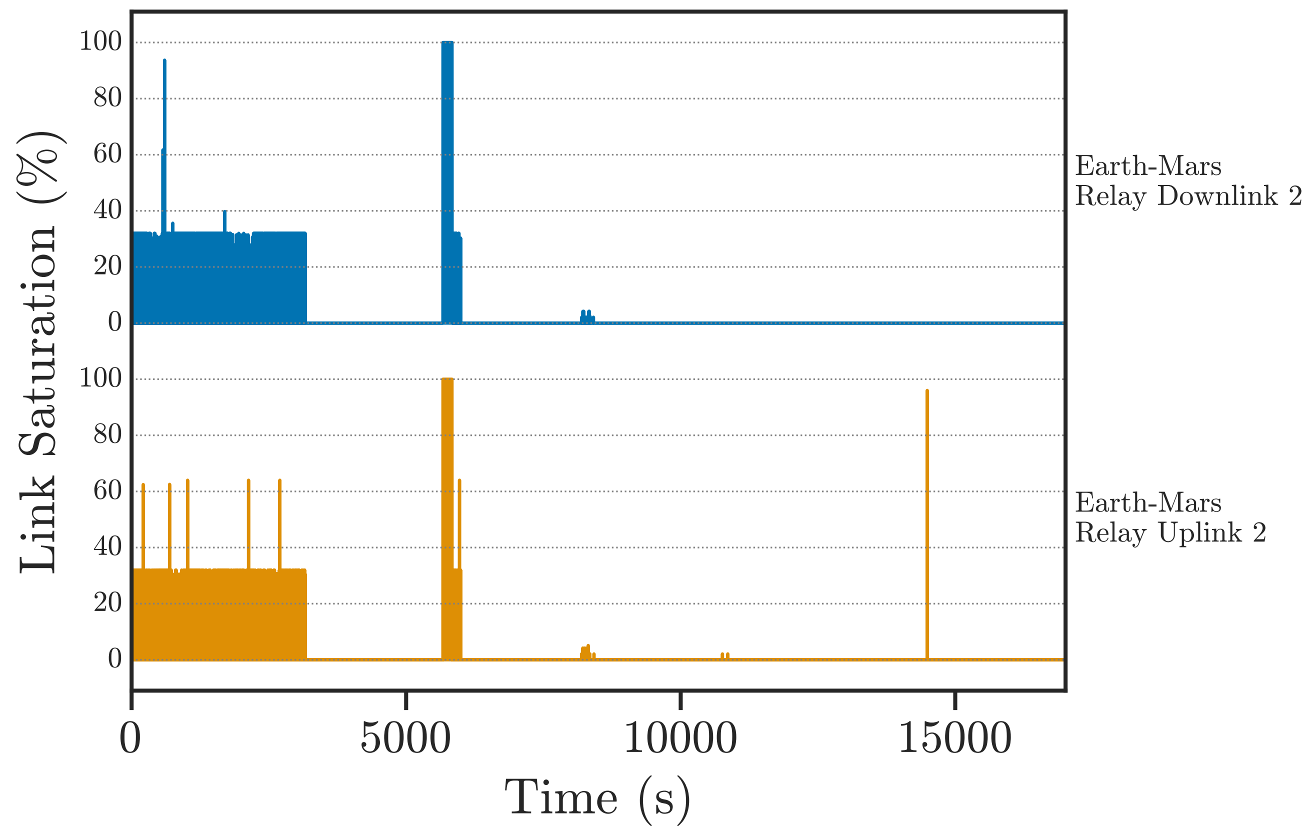


- DTN reference scenarios
  - Bursts of traffic when links become available to satisfy buildup of traffic
  - Store and forward improves delivery somewhat (unsurprising)
  - LTP guarantees delivery but with significantly more traffic and delays

Results

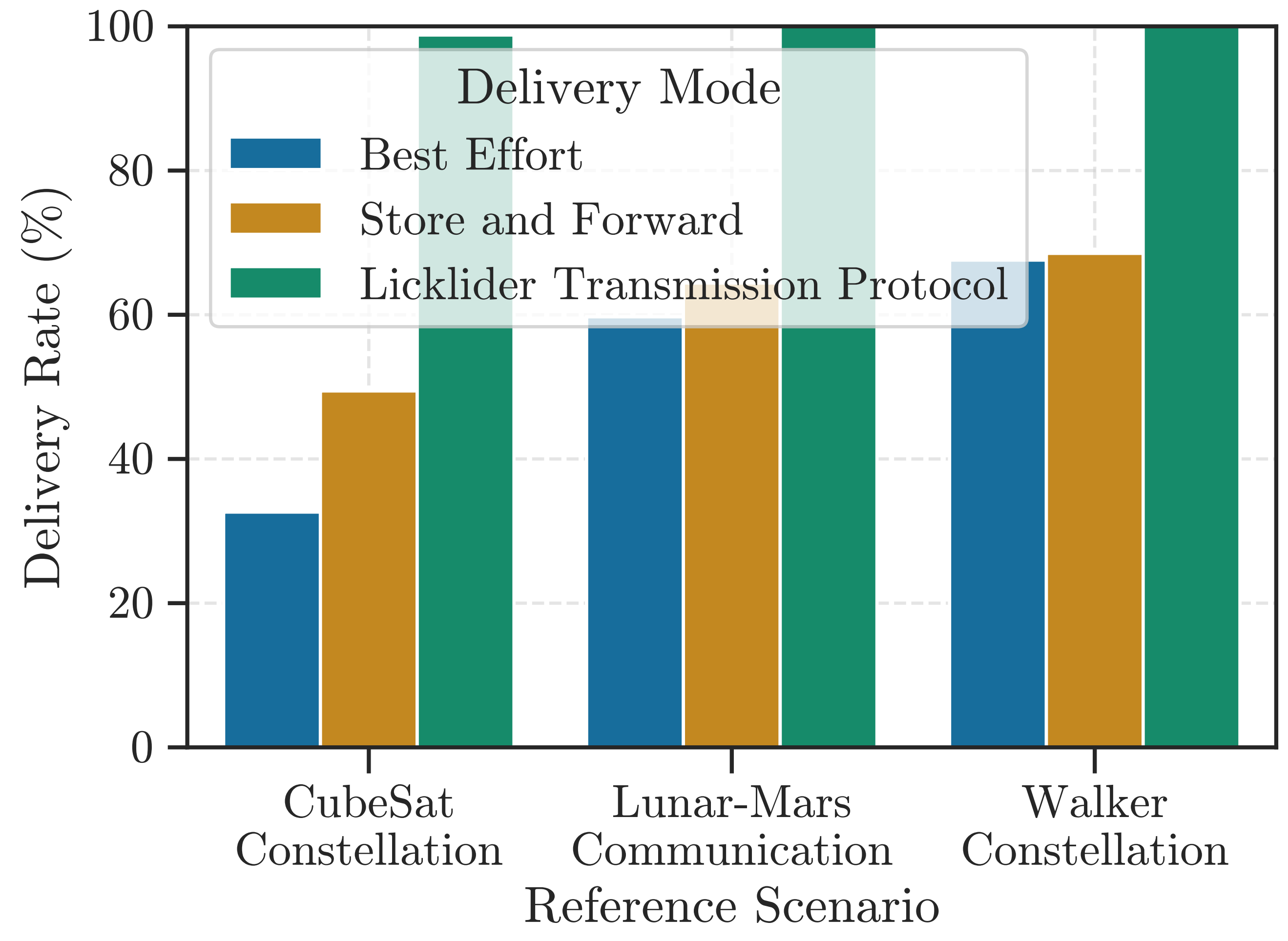


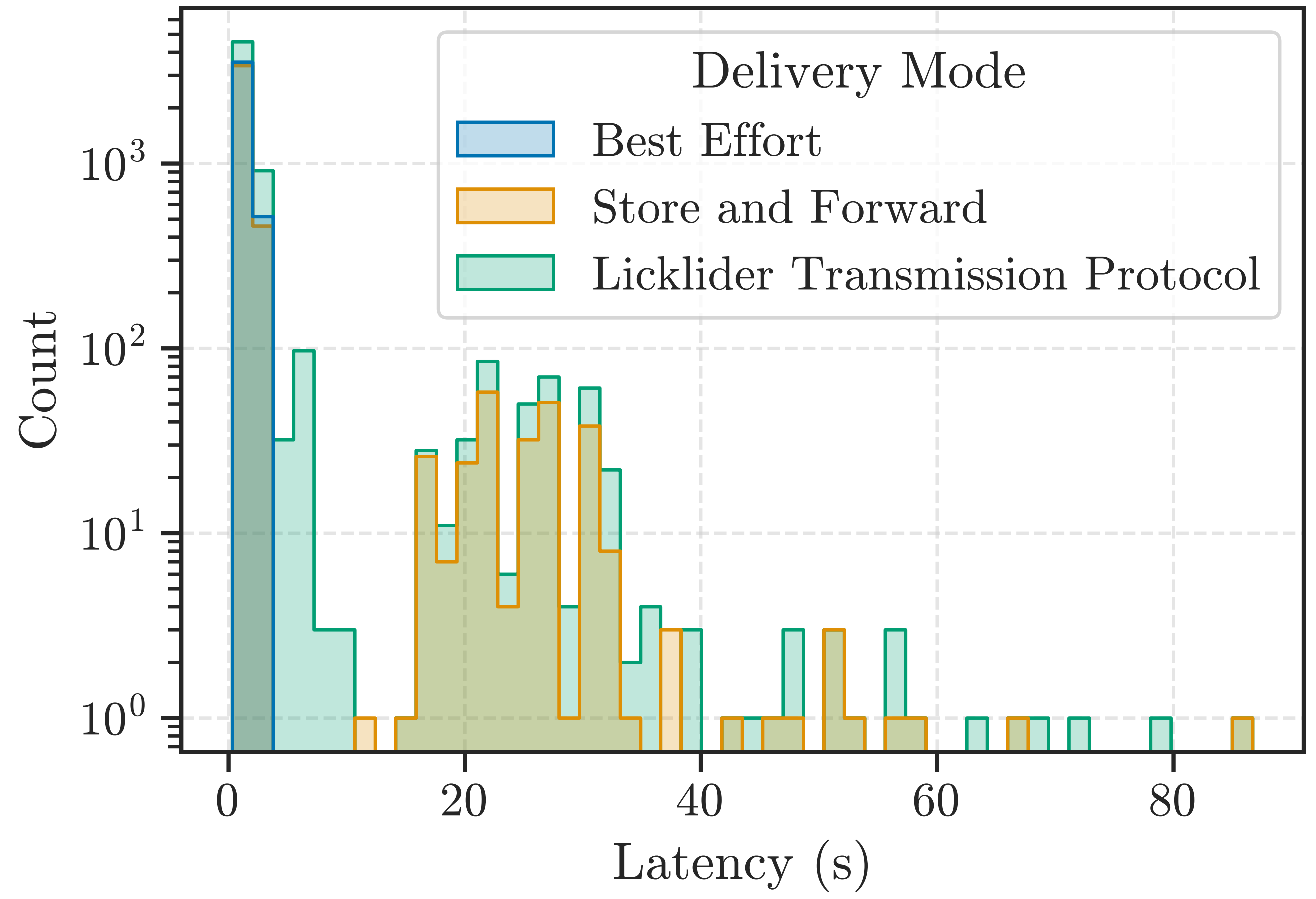


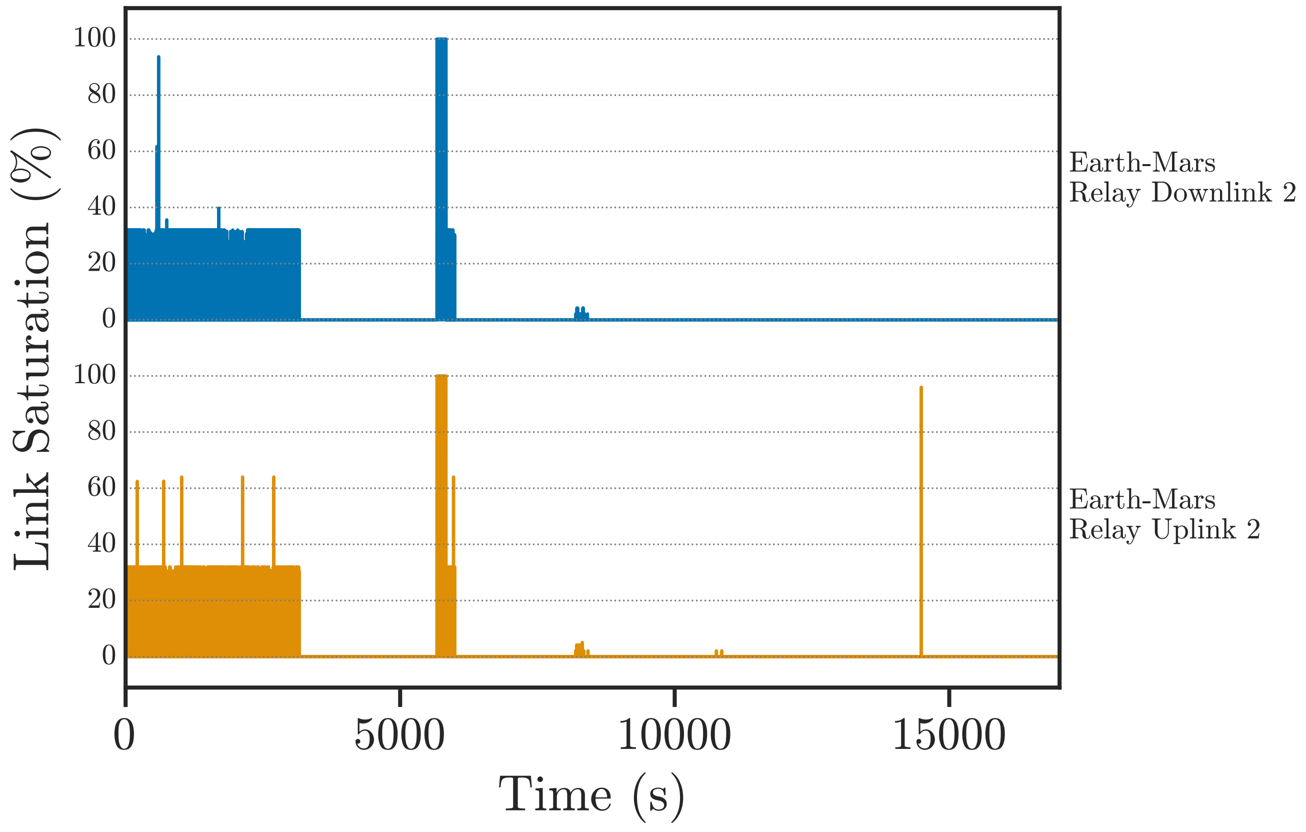


- DTN reference scenarios
- Custom scenarios

Results

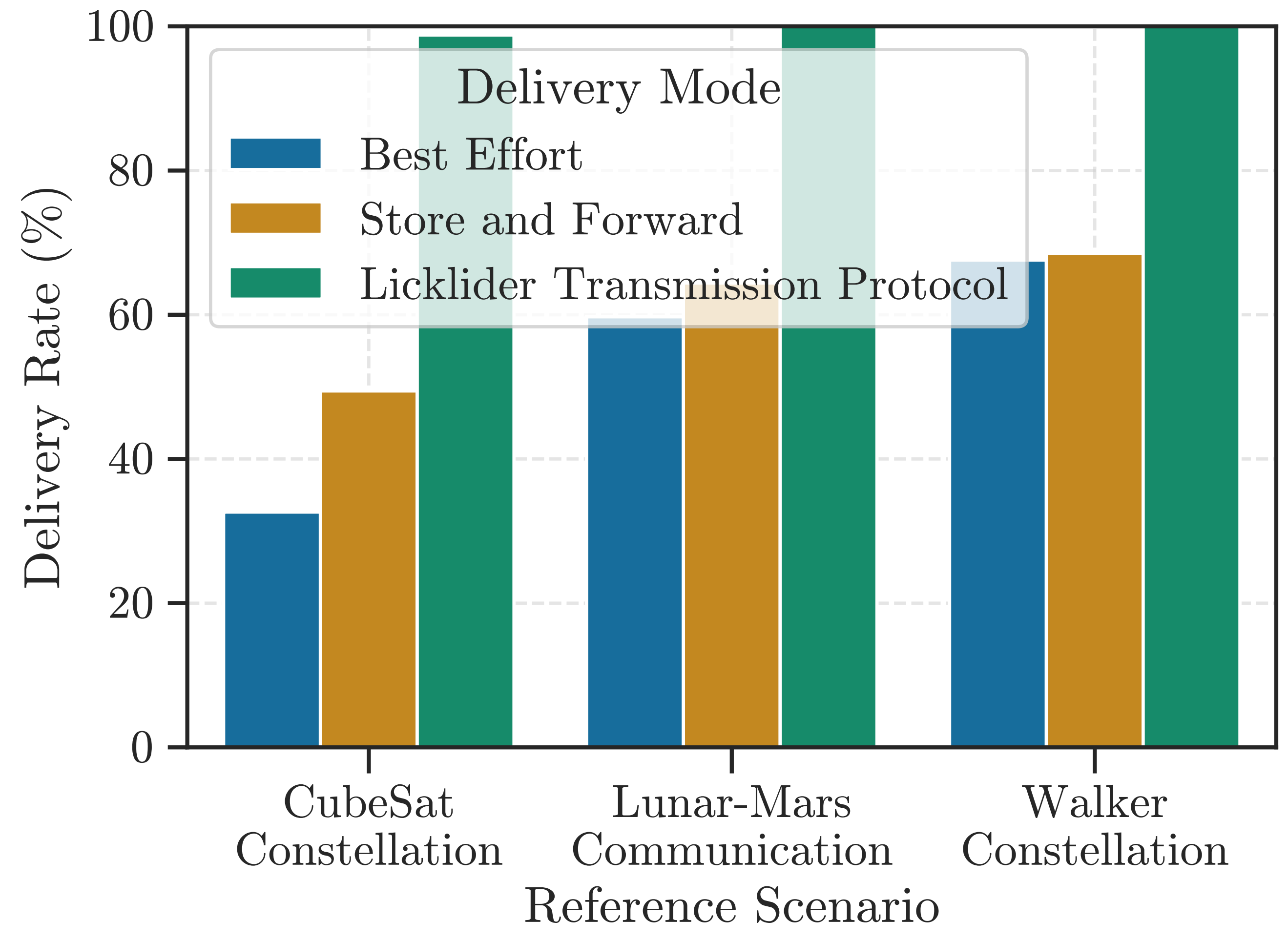


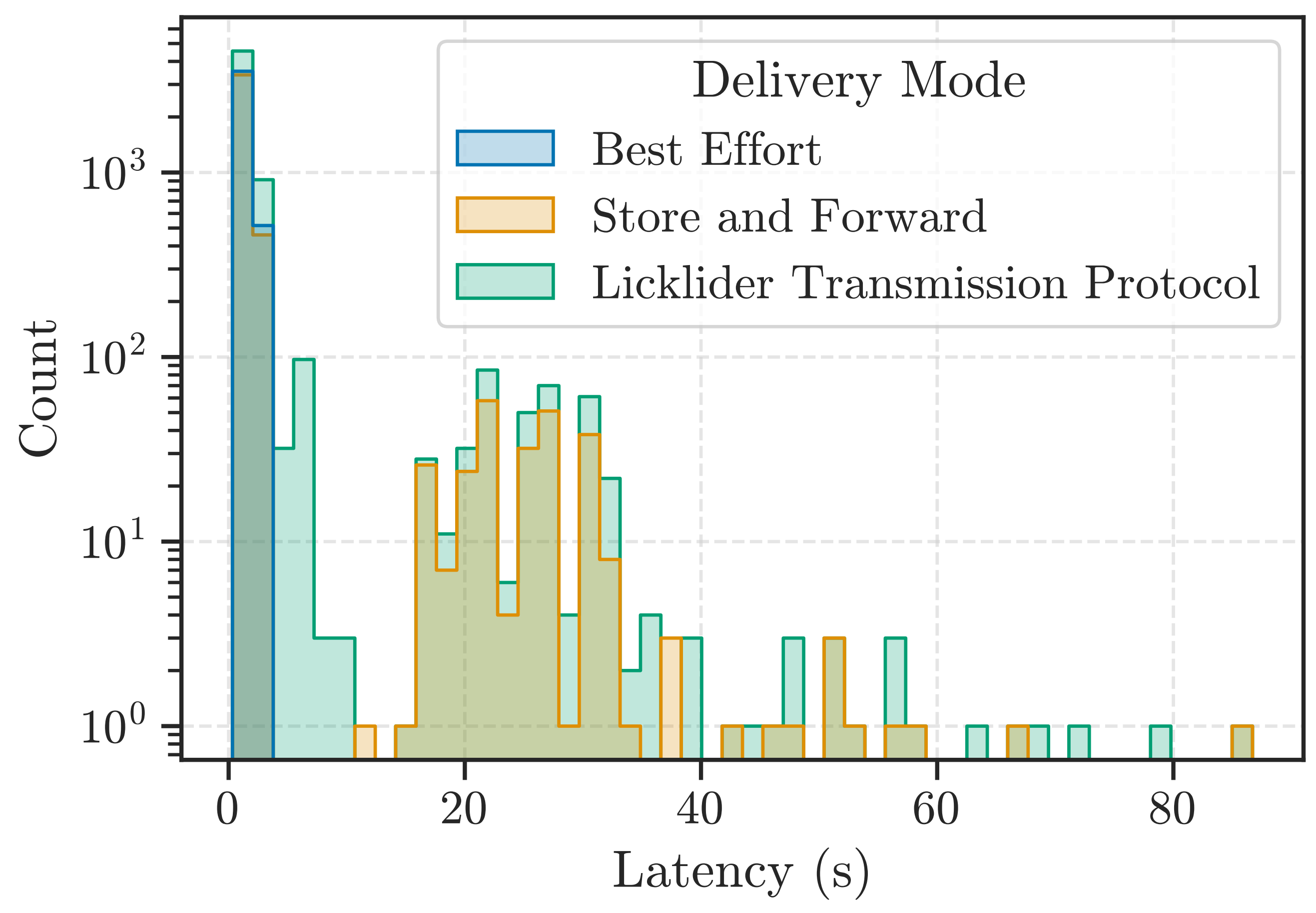


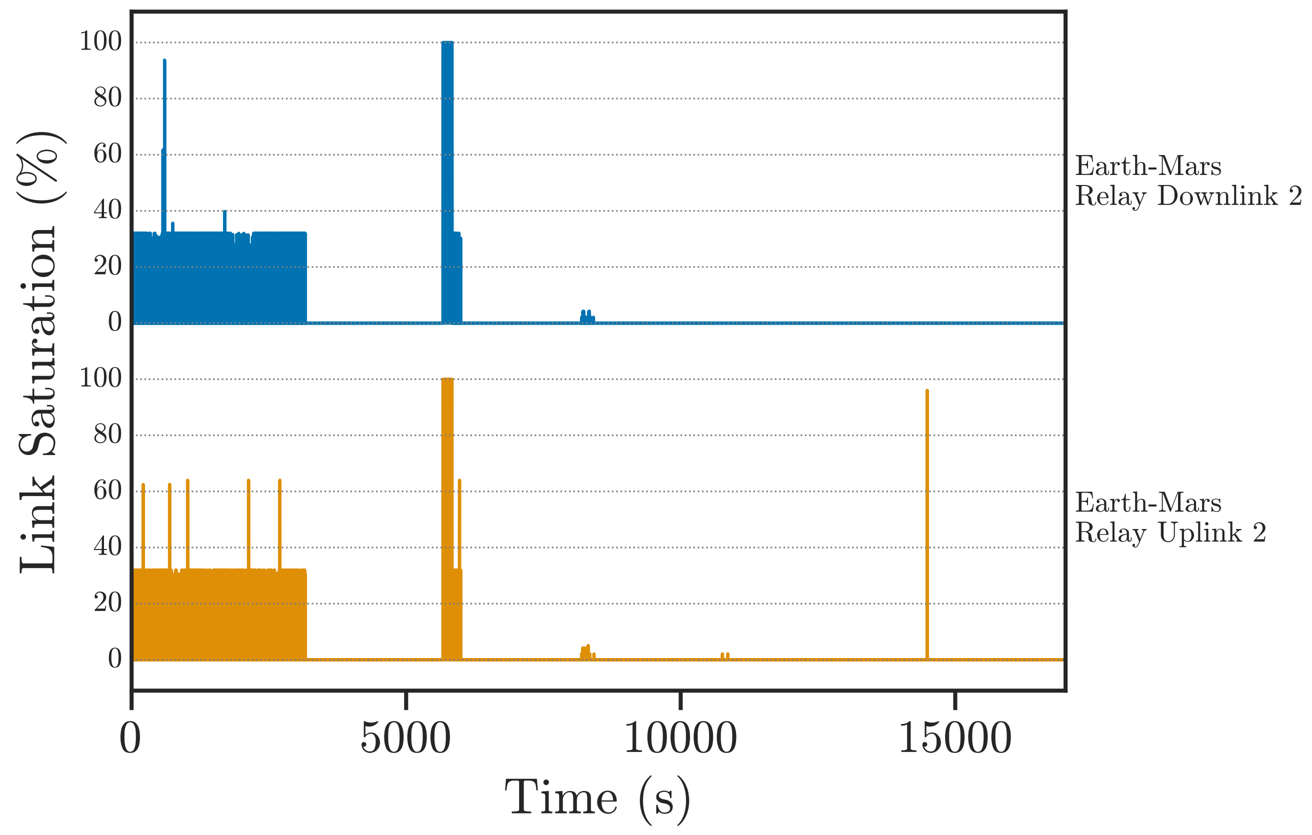


- DTN reference scenarios
- Custom scenarios
  - Less marked difference between best effort vs store and forward

RESULTS







- DTN reference scenarios
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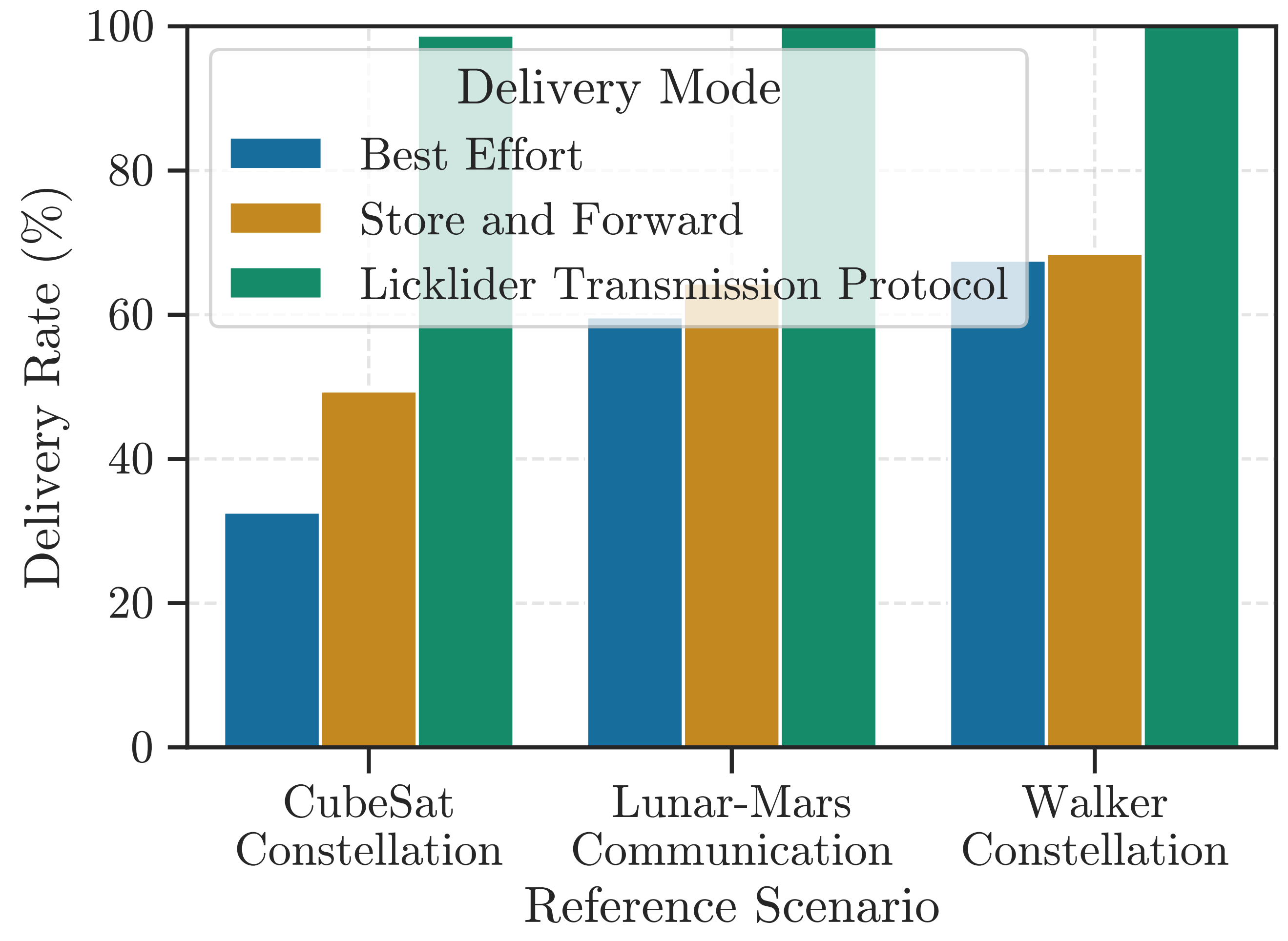
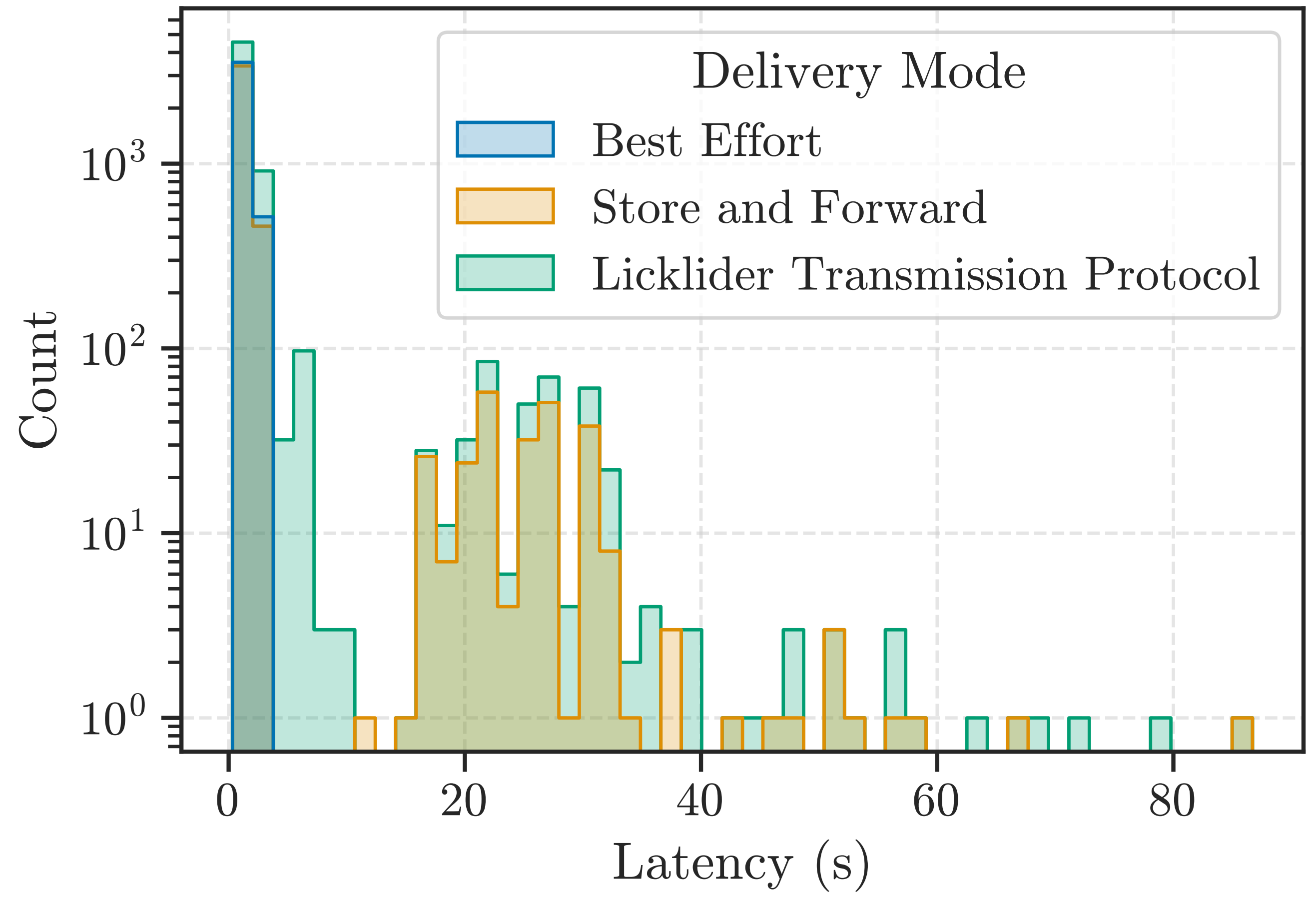
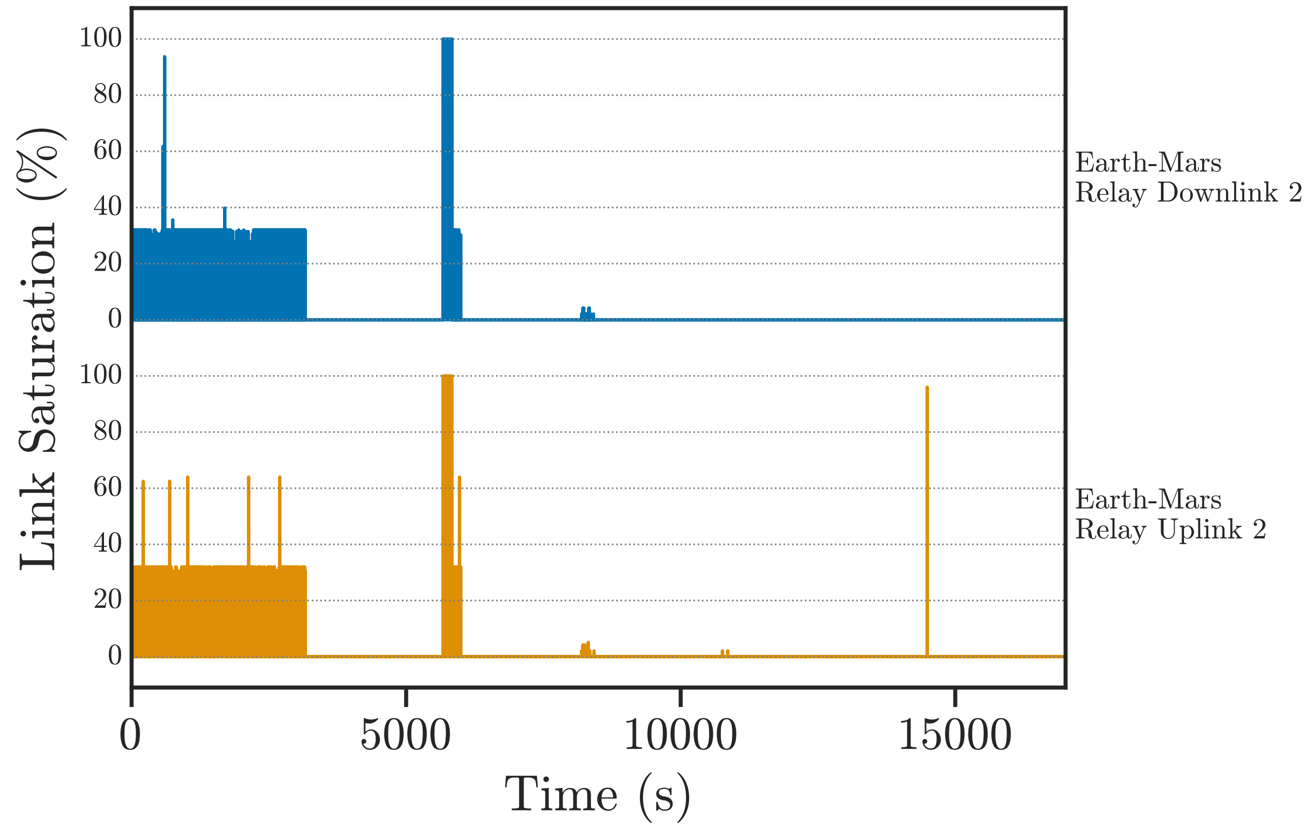
  - Less marked difference between best effort vs store and forward
  - LTP still the clear winner

Results

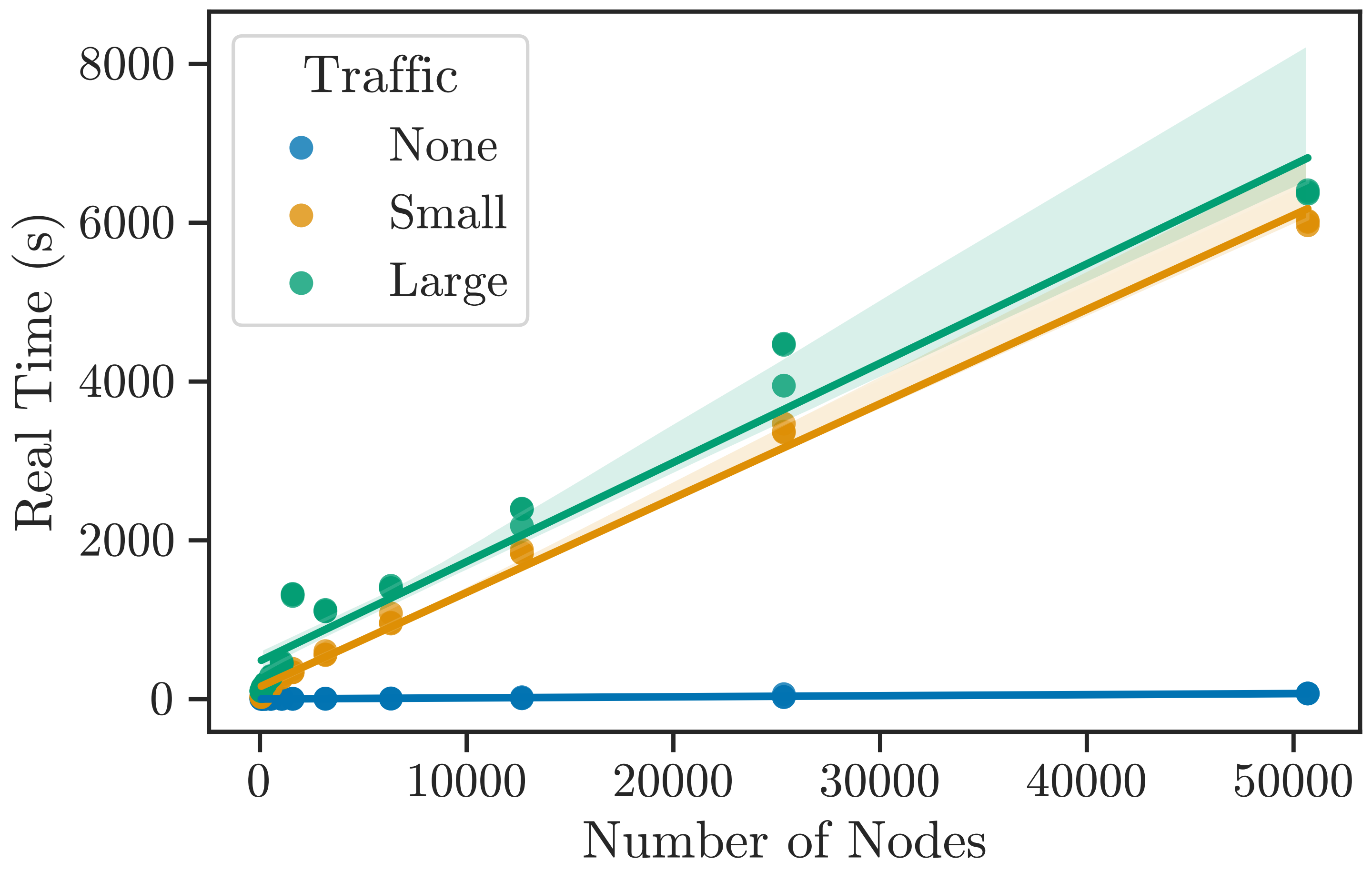


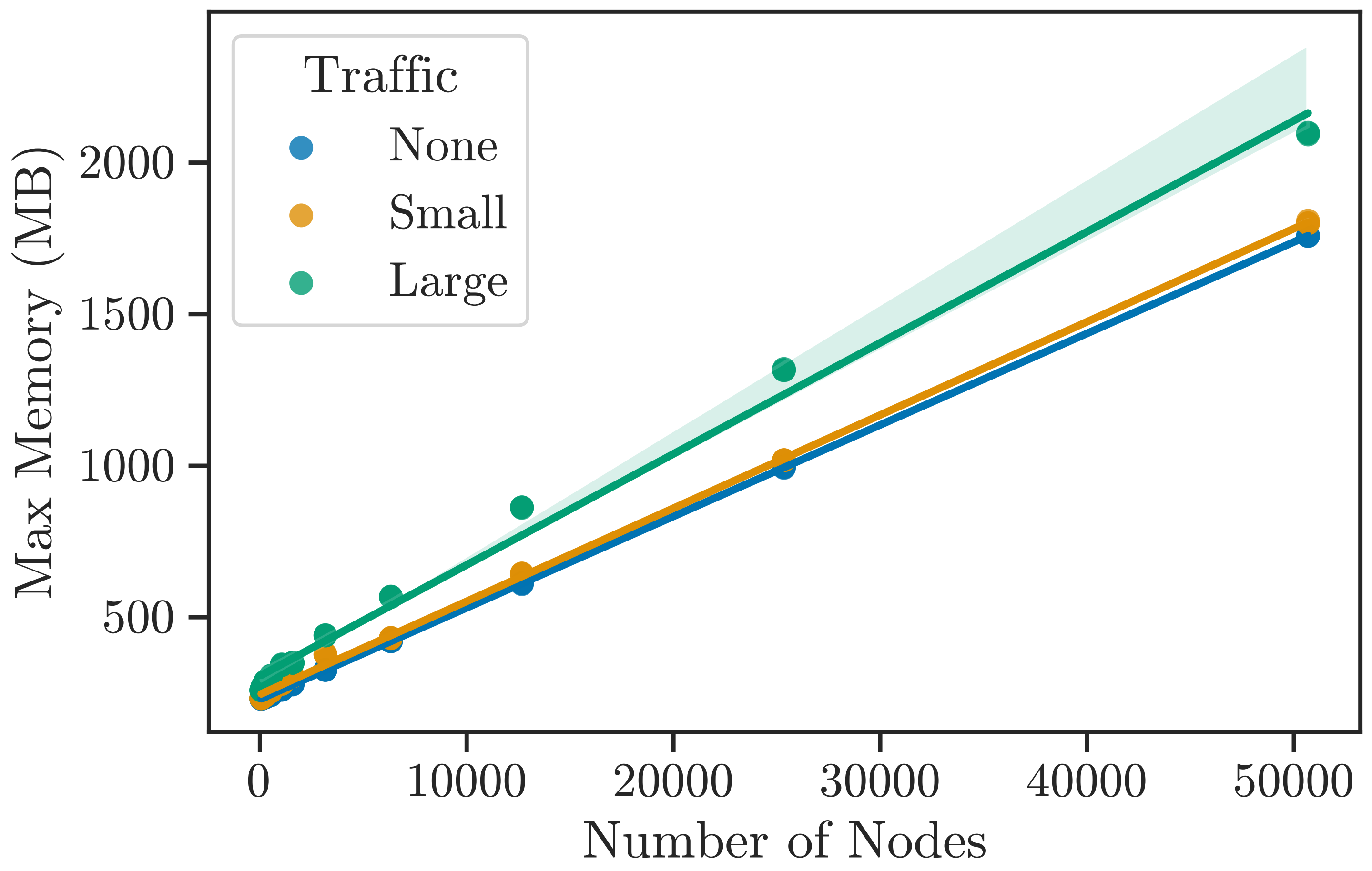




- DTN reference scenarios
- Custom scenarios
  - Less marked difference between best effort vs store and forward
  - LTP still the clear winner
  - Looking at relay links allows us to see if more bandwidth is required

Results





- DTN reference scenarios
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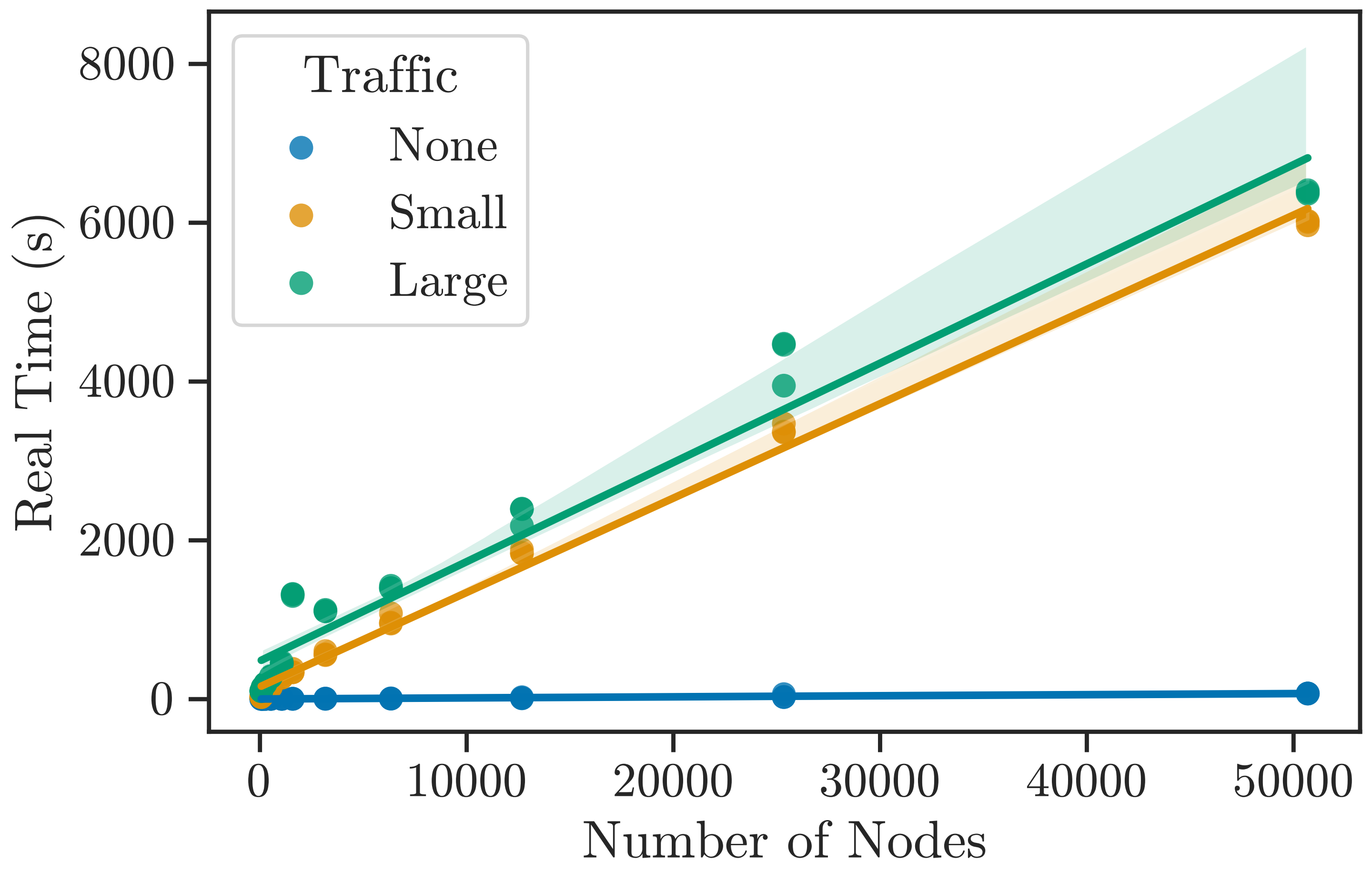

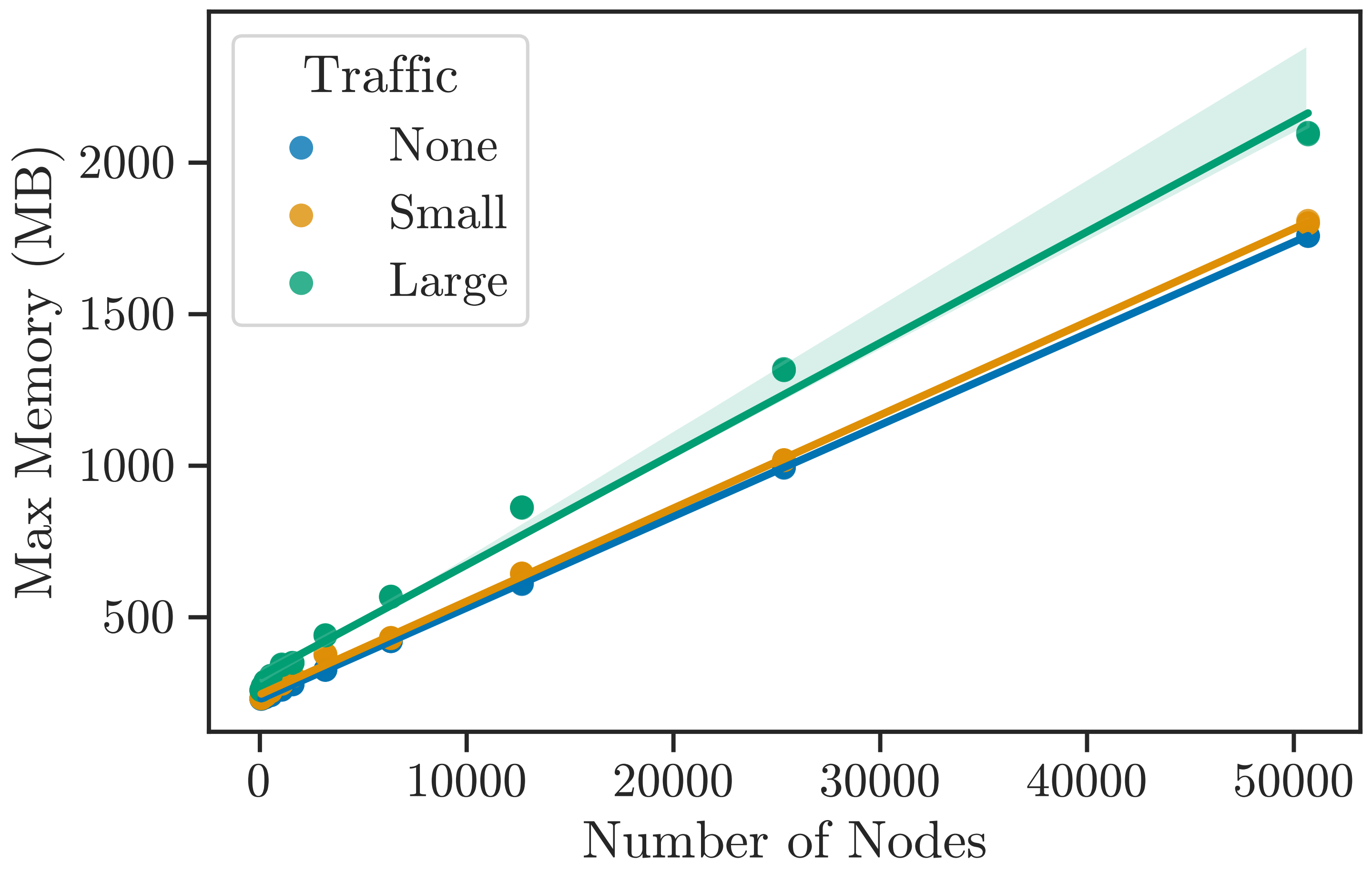

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  - Simulation handily scales to tens of thousands of nodes and beyond

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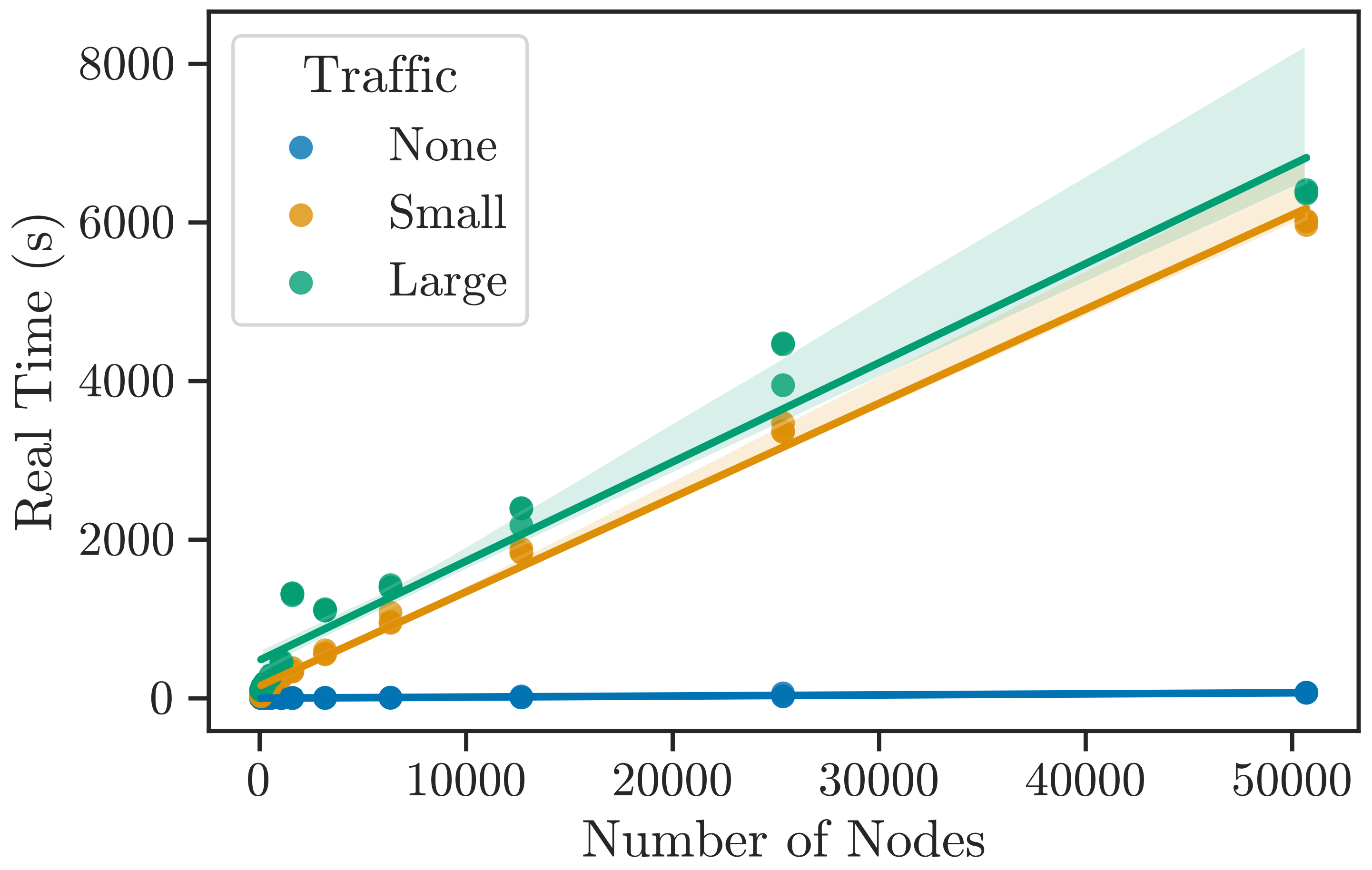
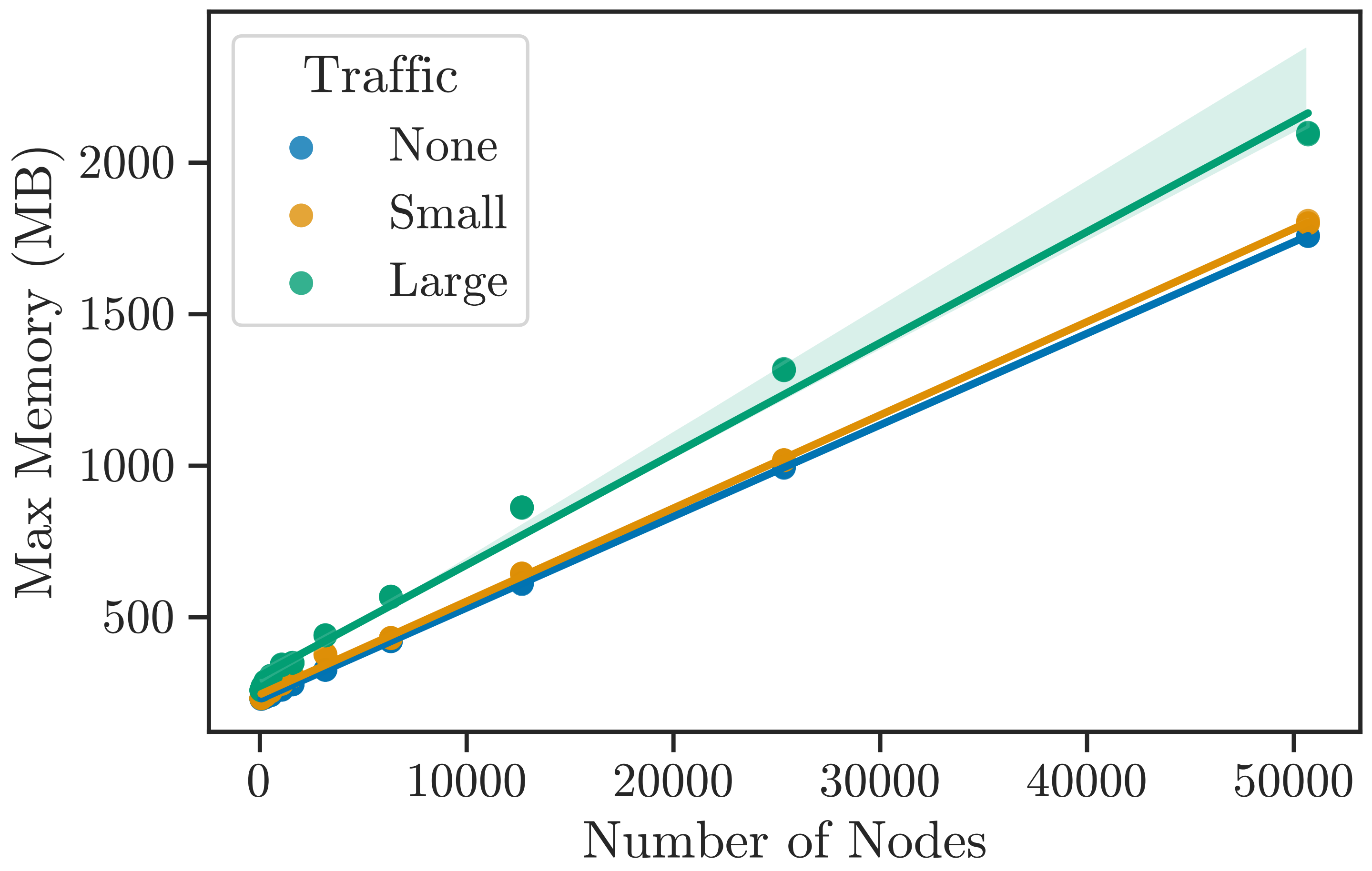
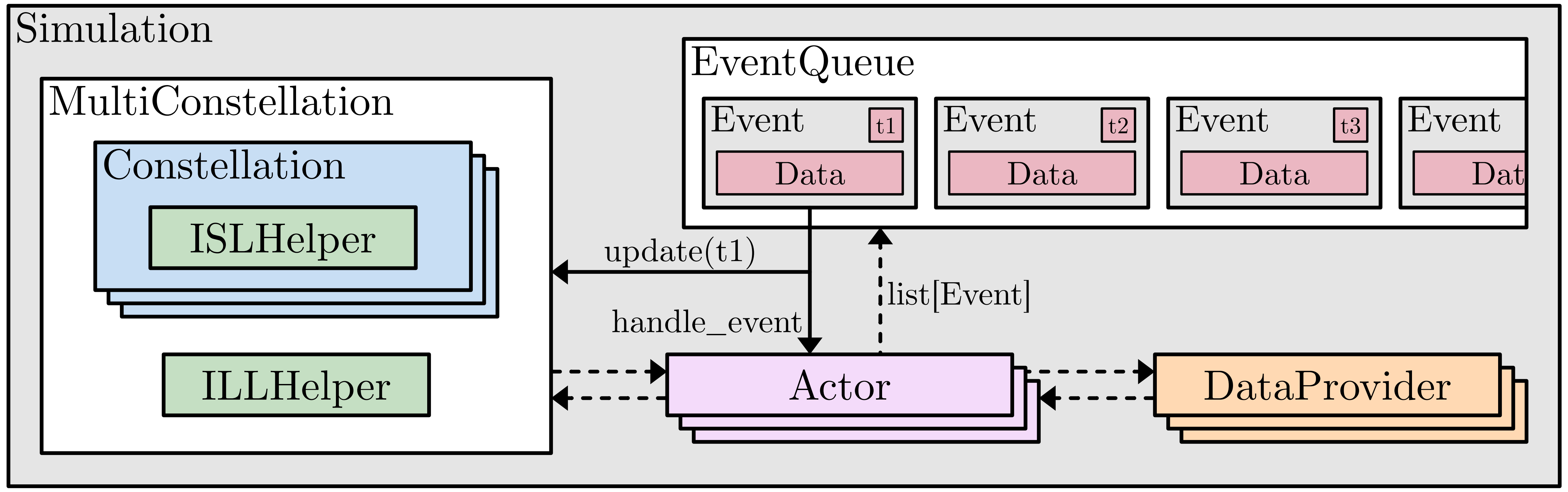




- DTN reference scenarios
- Custom scenarios
- Scalability
  - Simulation handily scales to tens of thousands of nodes and beyond
  - Traffic volume is the main driver of performance; simulation scale mostly affects memory

Extending DSNS

Modular architecture makes extensions very simple:



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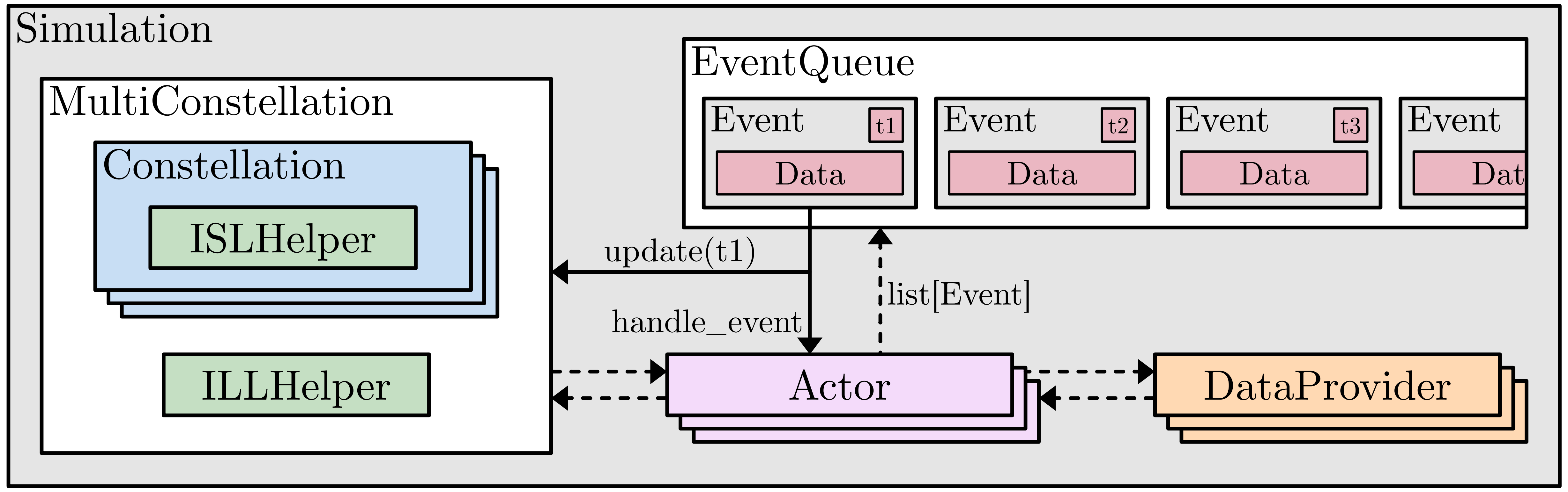

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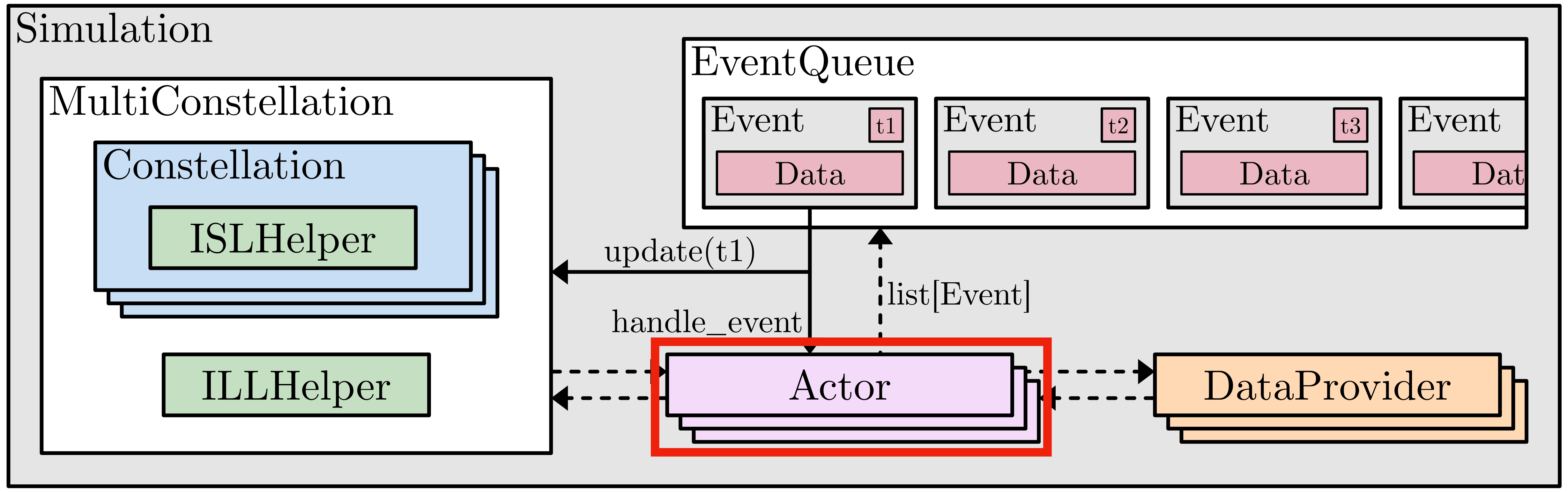
Extending DSNS



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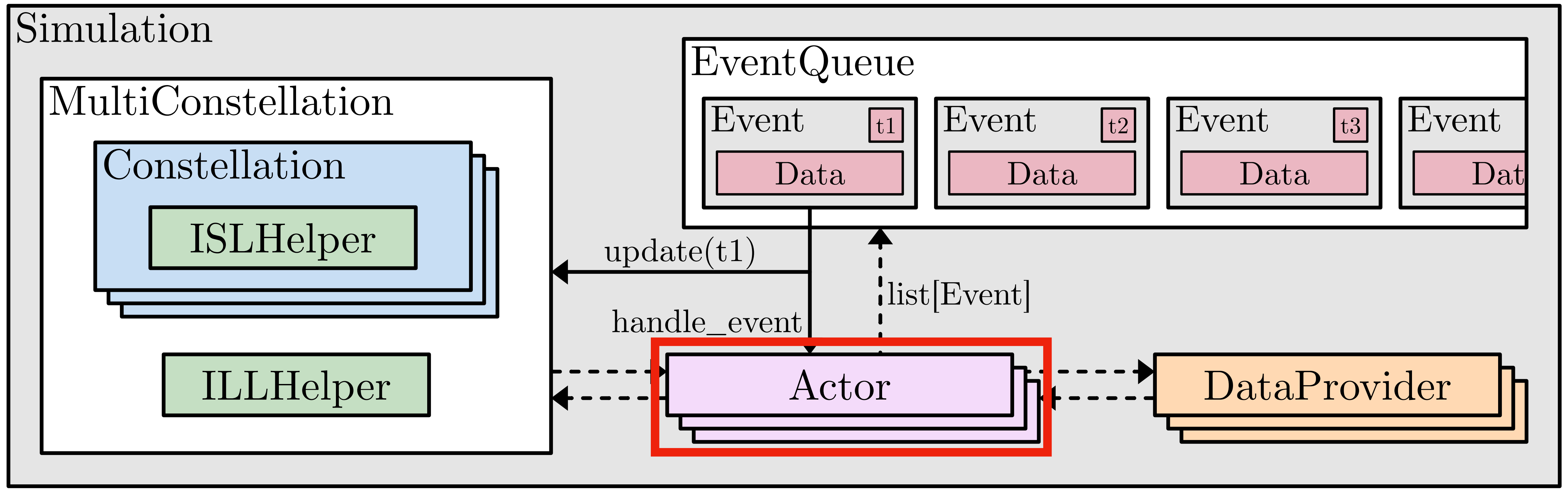
  - Actor to generate / respond to messages!

EXTENDING DSNS



Modular architecture makes extensions very simple:

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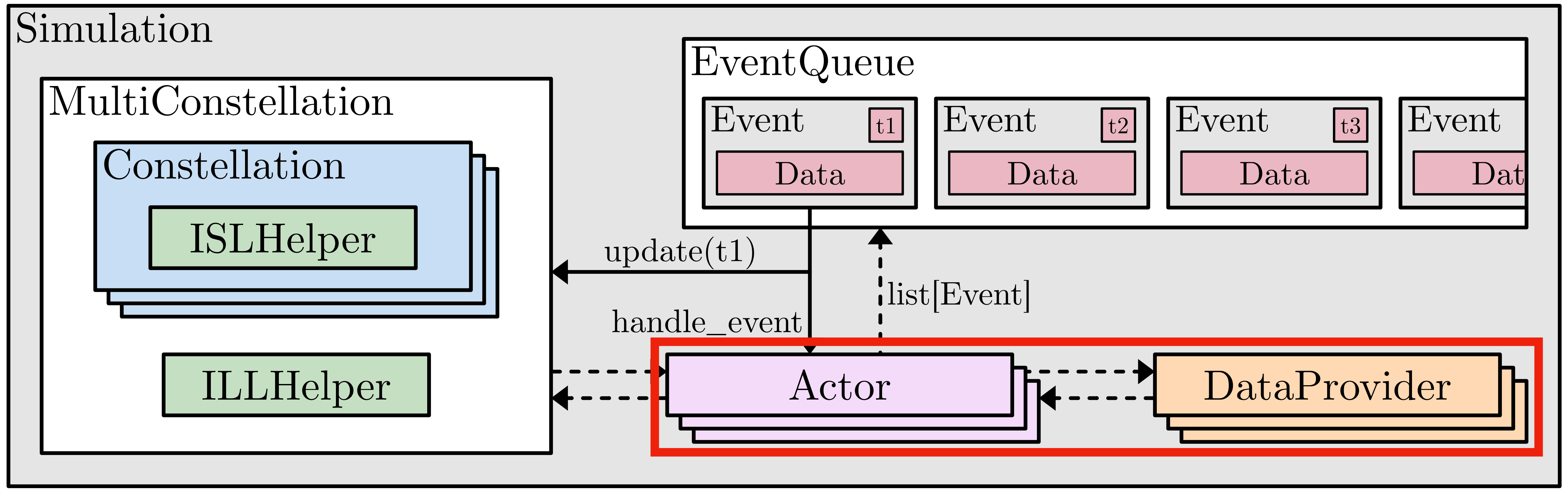

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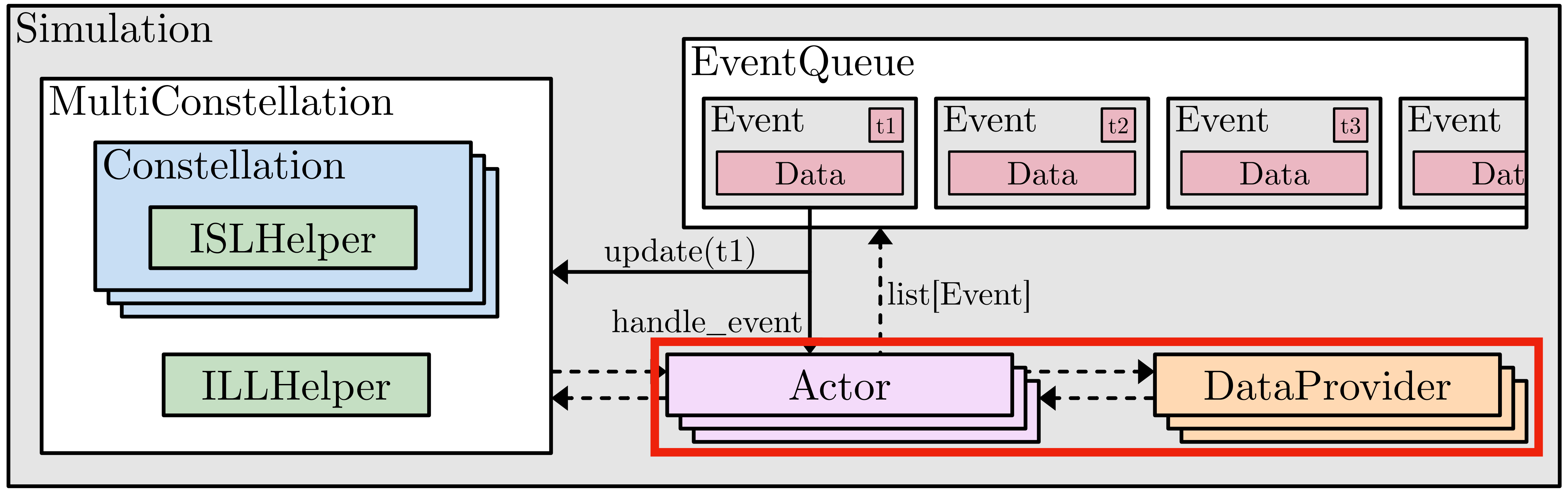

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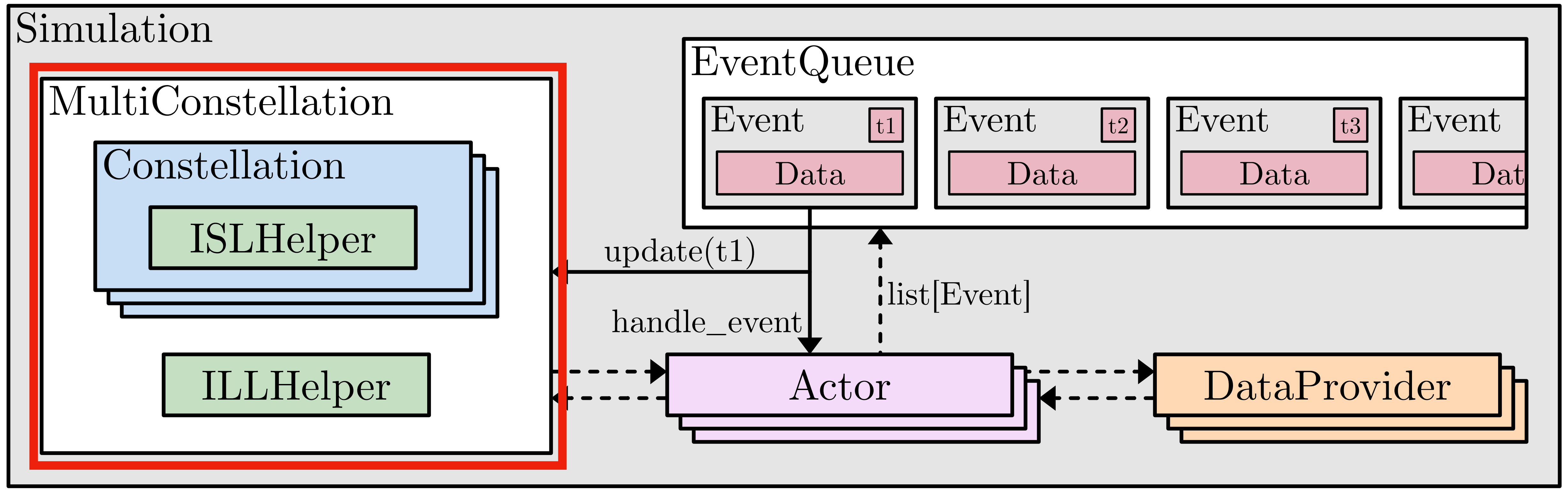

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    (or stitch together existing ones)

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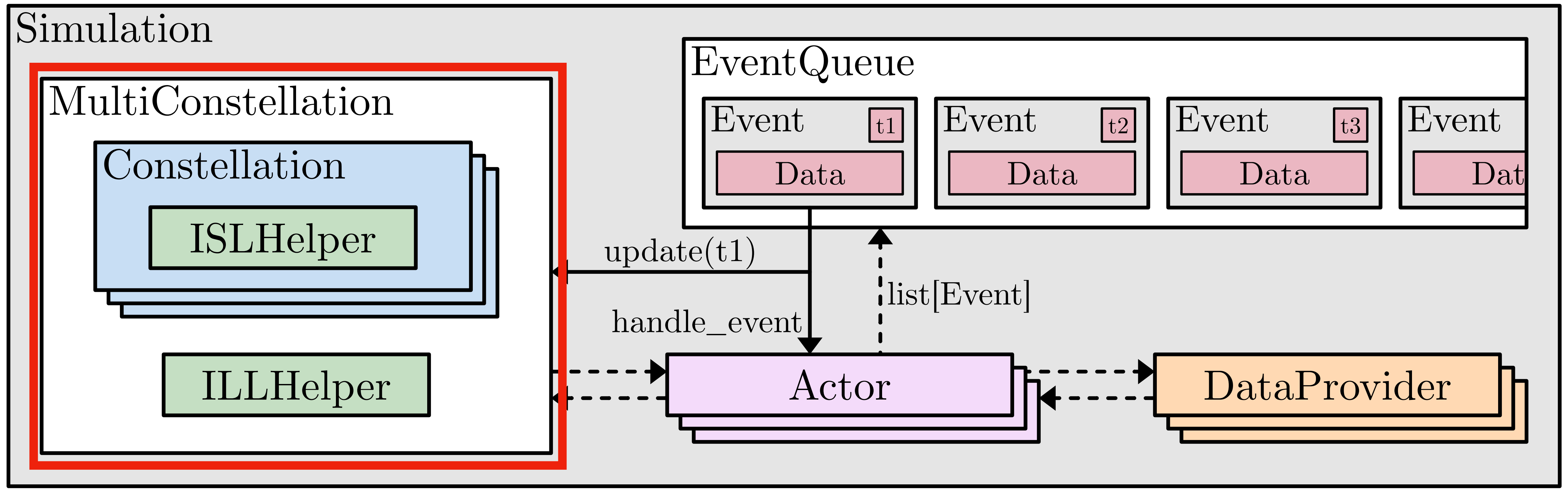

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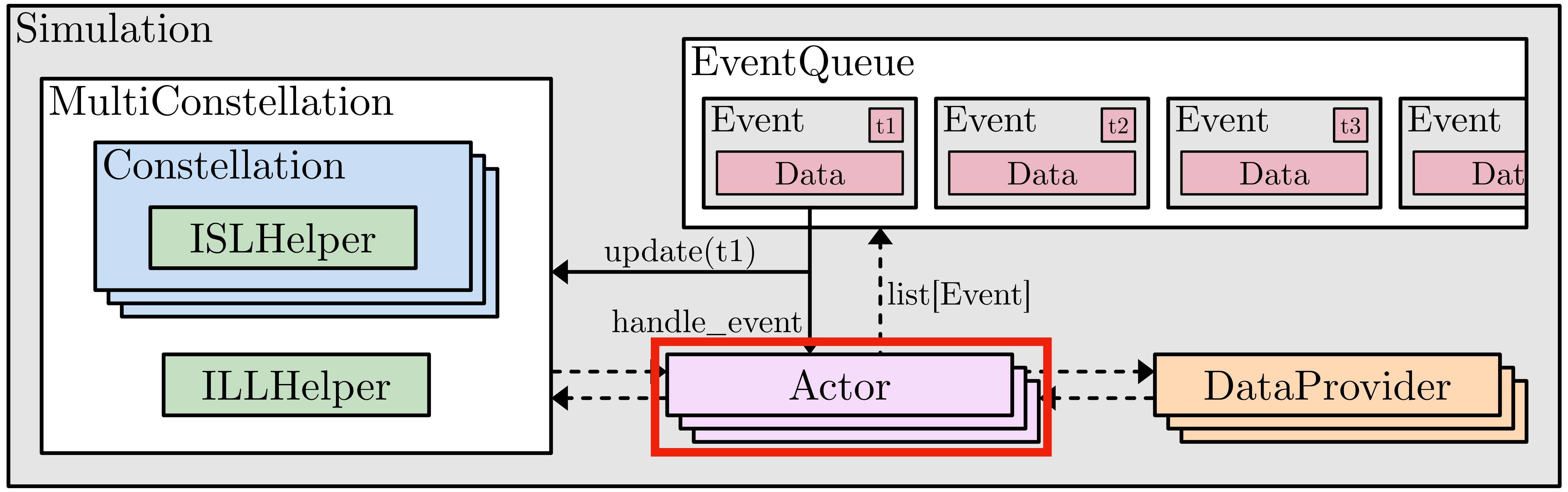

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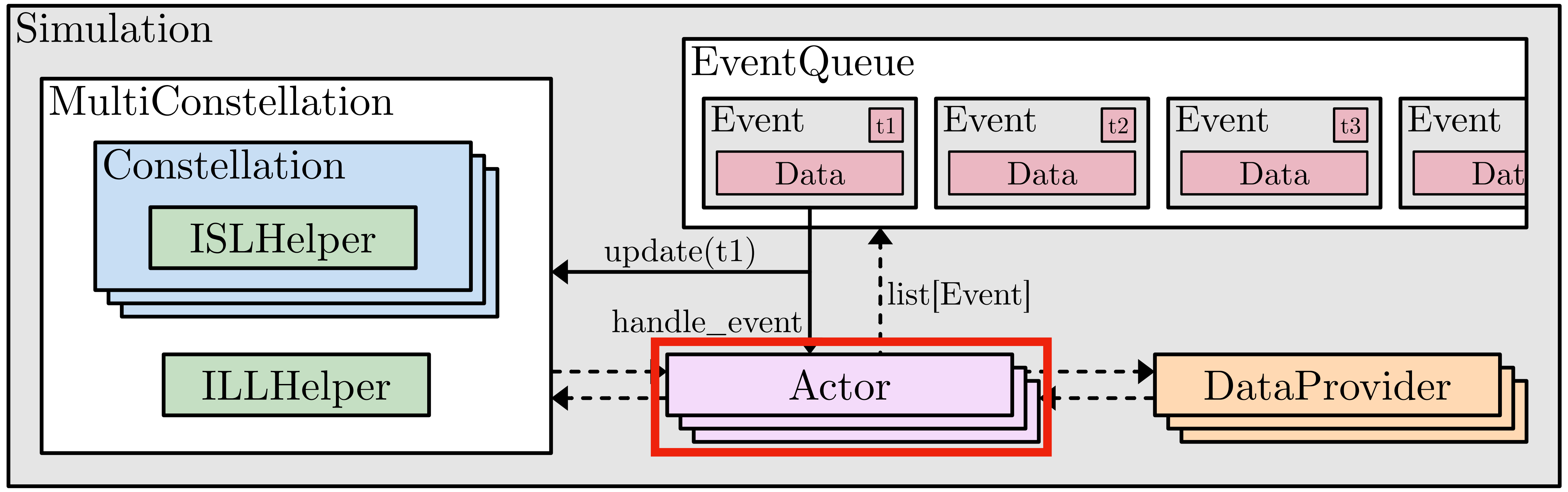

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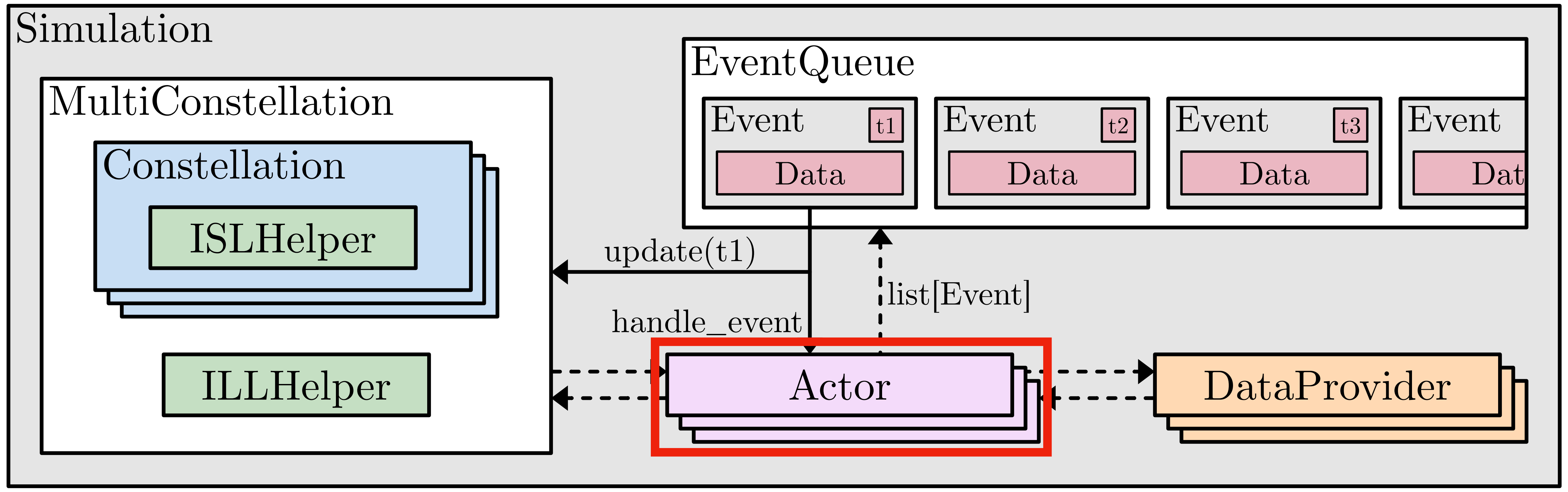

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  - LossConfig for global/targeted message loss
  - Dynamically adjust bandwidth constraints, message loss rate
  - Flooding, bandwidth exhaustion attacks via TrafficFloodActor

Use Cases

Existing use cases:

Use Cases

Existing use cases:

- Optimising PKI in interplanetary networks[1]

[1] Joshua Smailes, Sebastian Köhler, Simon Birnbach, Martin Strohmeier, Ivan Martinovic. "KeySpace: Enhancing Public Key Infrastructure for Interplanetary Networks".

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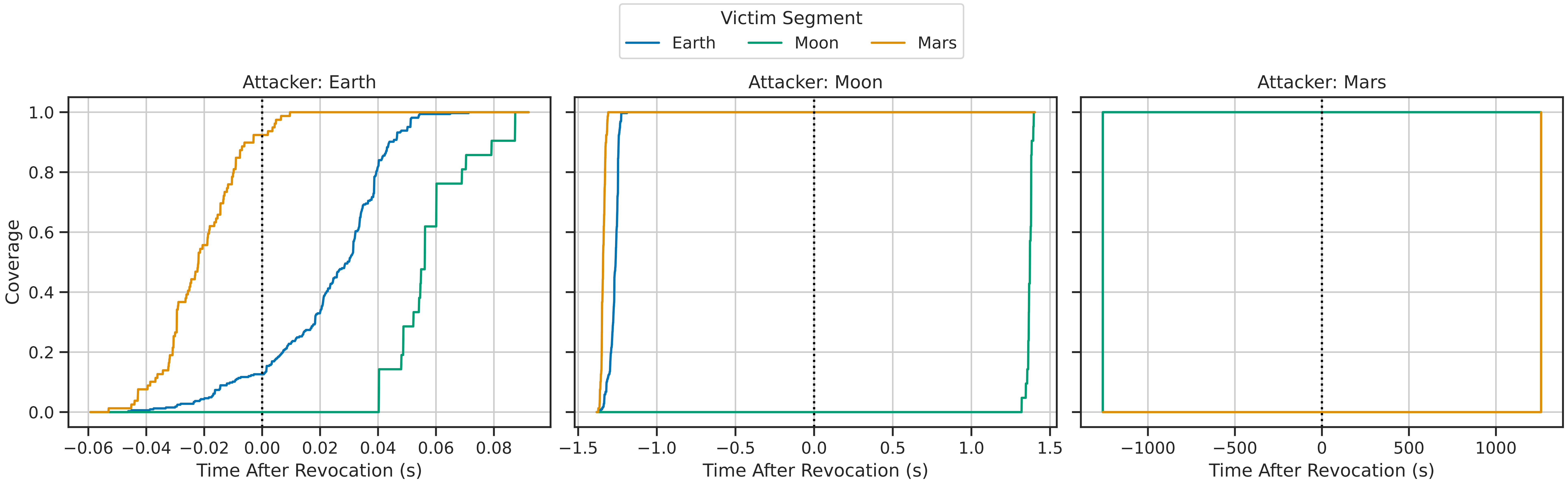

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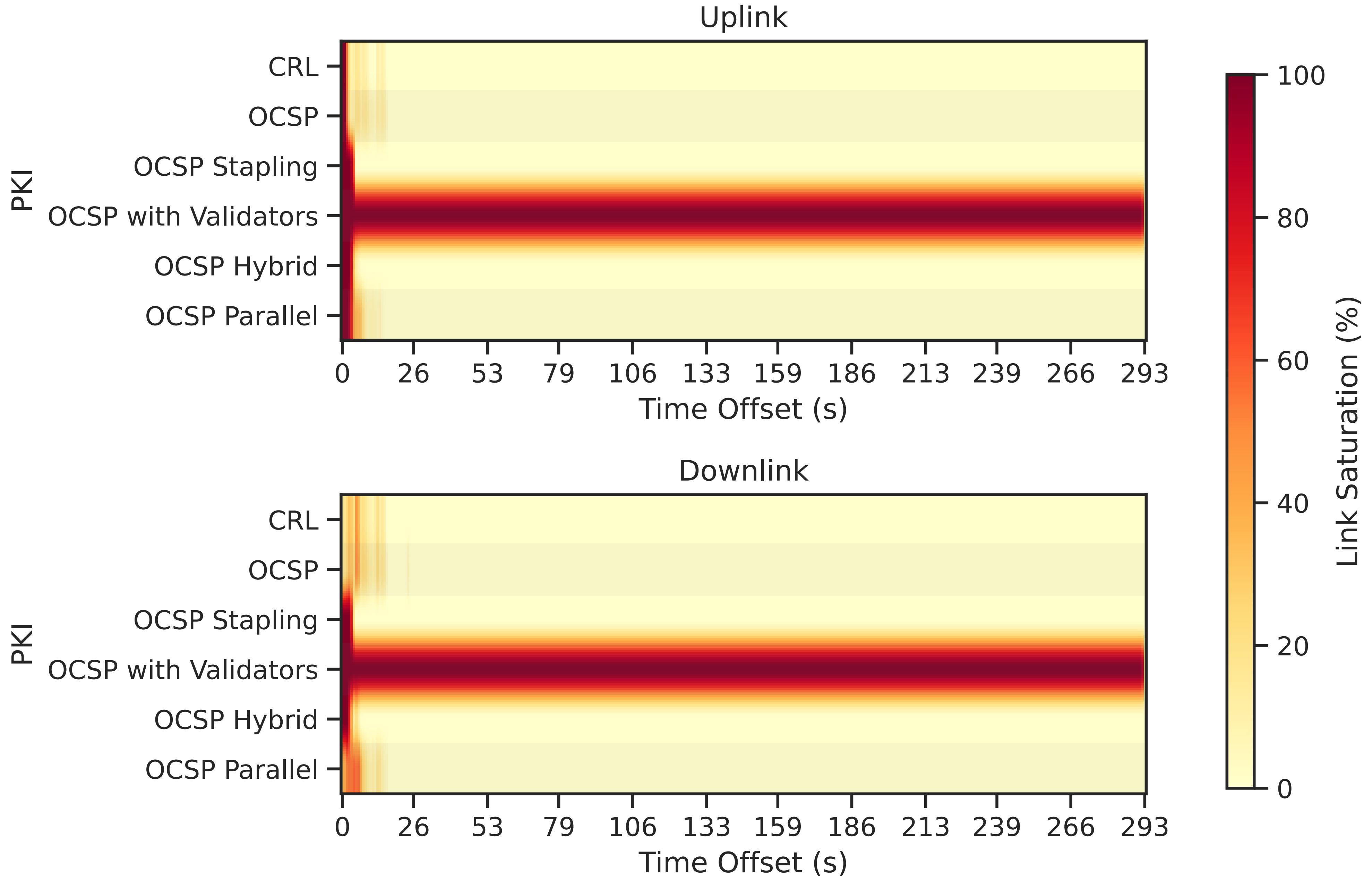

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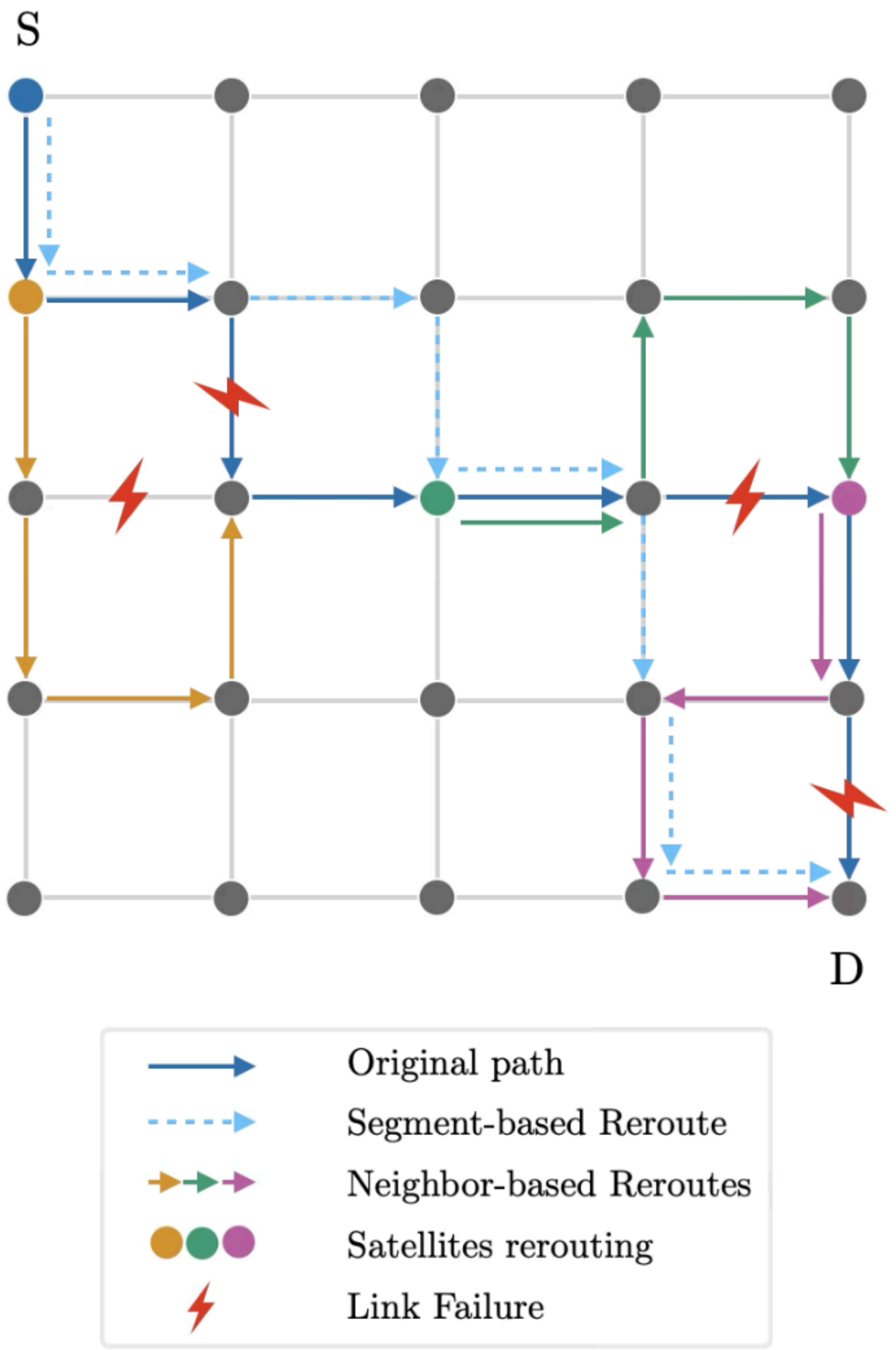

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Future uses:

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- Integrate with real-world hardware?

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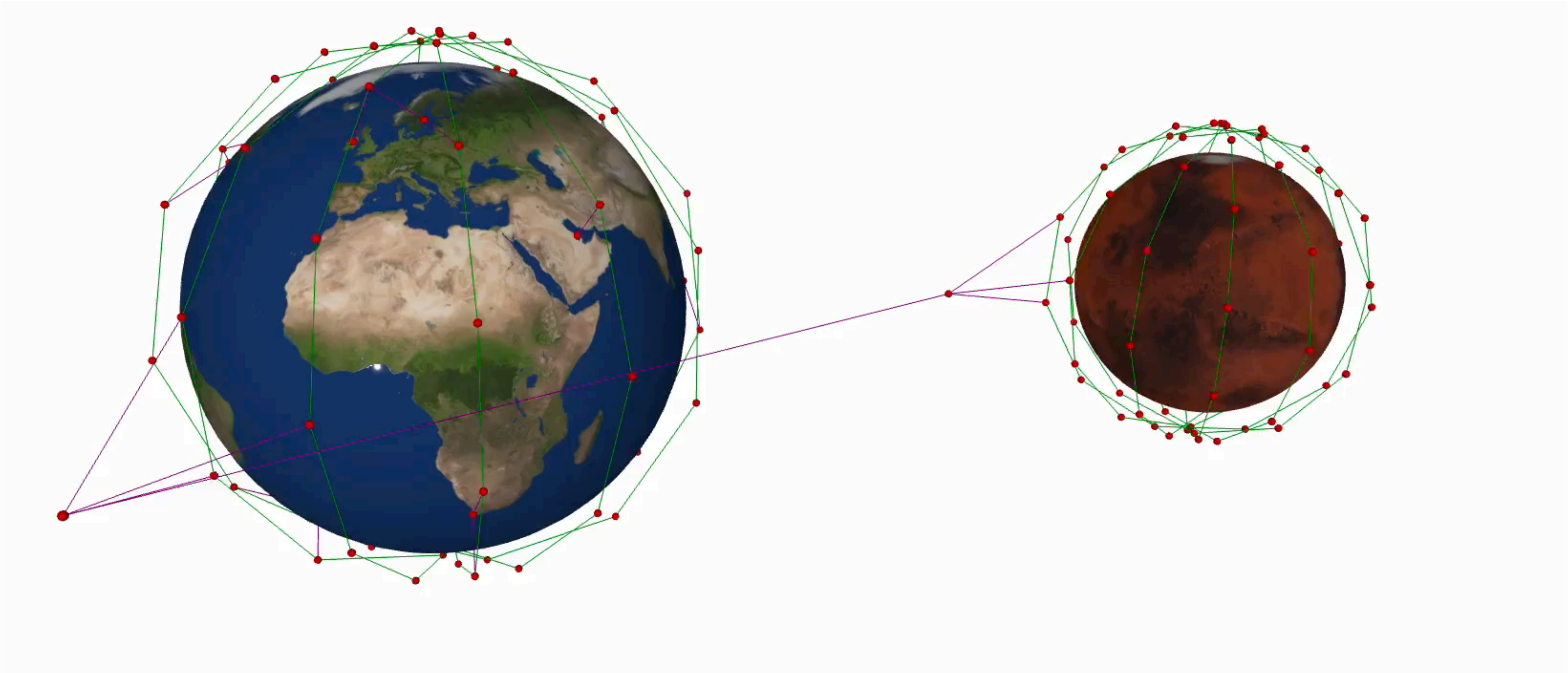
Thank you!

Any questions?

DSNS

github.com/ssloxford/DSNS



Get in touch:

Joshua Smailes

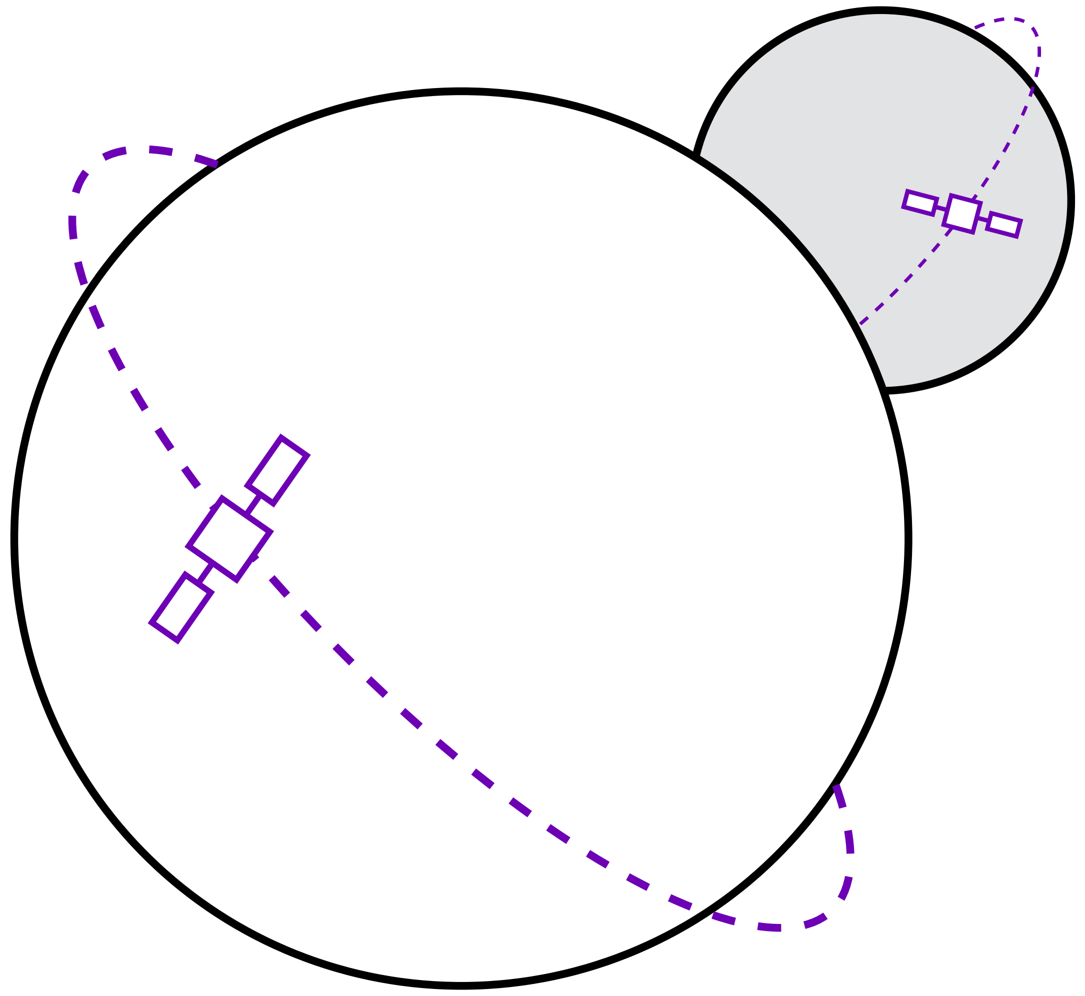
Systems Security Lab, University of Oxford

joshua.smailes@cs.ox.ac.uk

Image: NASA

THANK YOU!

Any questions?



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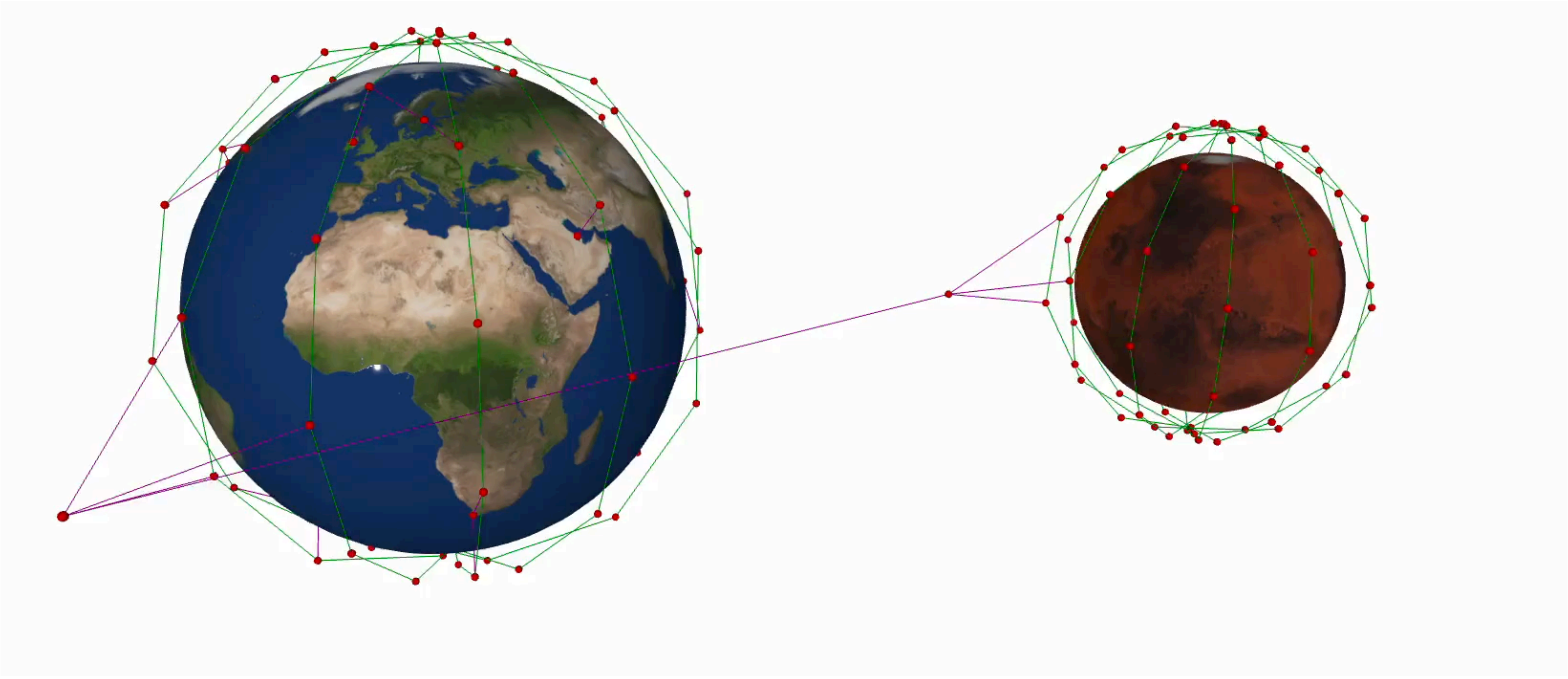

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