Lifespan-Aware Contact Plan Design

for Interplanetary Free-Space Optical Networks

Alejandro Toledo
UNC, Argentina

Jason Gerard · Sandra Céspedes
Concordia University, Canada

Juan A. Fraire
Inria · INSA Lyon, France / CONICET, Argentina

WiSEE 2026 — STINT

The bottleneck is the pipe home

75%

of Mars Relay Network mission data reportedly dropped at peak load
not for lack of collection, but for lack of downlink

1. **Optical wins on capacity**

   Free-space laser delivers Gbps–Tbps at lower **size**, **weight**, **power** and **cost** than RF.

2. **Optical costs you a narrow beam**

   Links require **pointing**, **acquisition** and **tracking** (PAT) before a single bit moves.

3. **So links have to be scheduled carefully**

   Every link opportunity must be committed to in advance.
   That is **Contact Plan Design** (CPD).

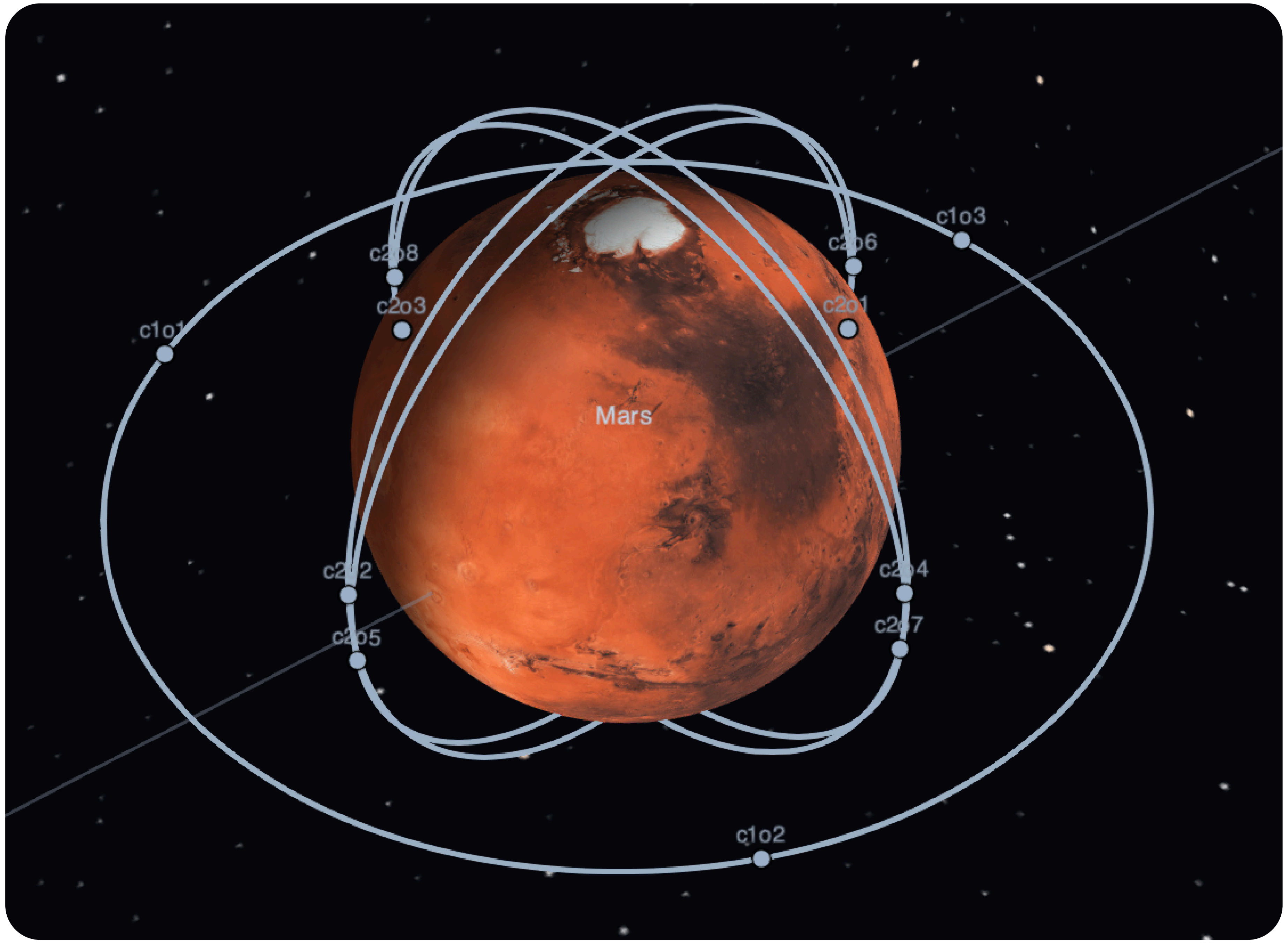
Source: R. Gladden, E. Pereira, and B. Sauer, "Lessons learned from the mars relay network: Considerations for future relay networks," in 2024 IEEE Aerospace Conference, 03 2024, pp. 1–16.

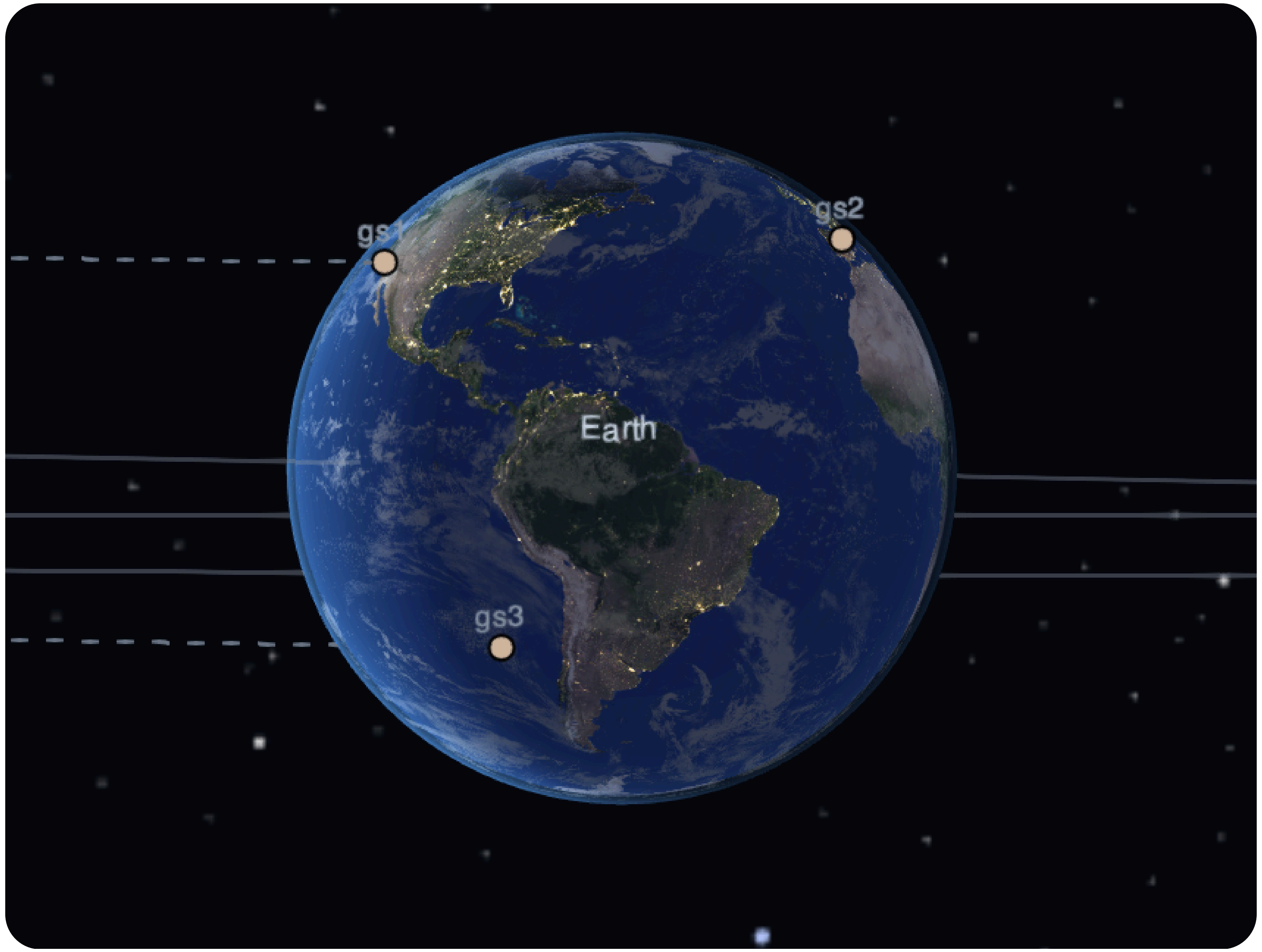
The empty gap

	ignores energy	models energy
optical interplanetary	**LLS** Gerard et al., WiSEE 2024 Max-flow capacity (ΔC), end-to-end aware, energy-blind	**THIS WORK** RTG decay + battery depletion + network capacity, in one scheduler
LEO/terrestrial RF	Other works . . .	**Battery-aware CPD** Fraire et al., 2020 State-of-charge for LEO, solar recharge, RF

System model

Mars science orbiters → Mars relay → optical ground stations at DSN sites

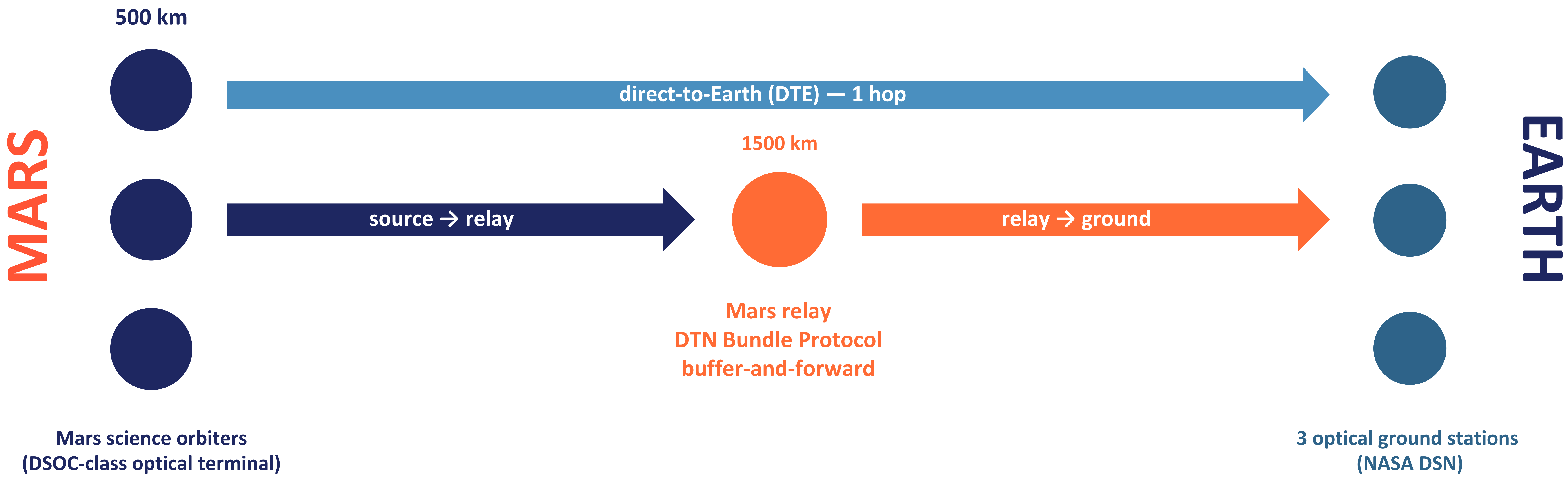




contact-plan-designer.space

System model

Mars science orbiters → Mars relay → optical ground stations at DSN sites



ONE LASER PER NODE

at most one contact per node per slot — every scheduled contact is an exclusive commitment

TWO PATH TYPES

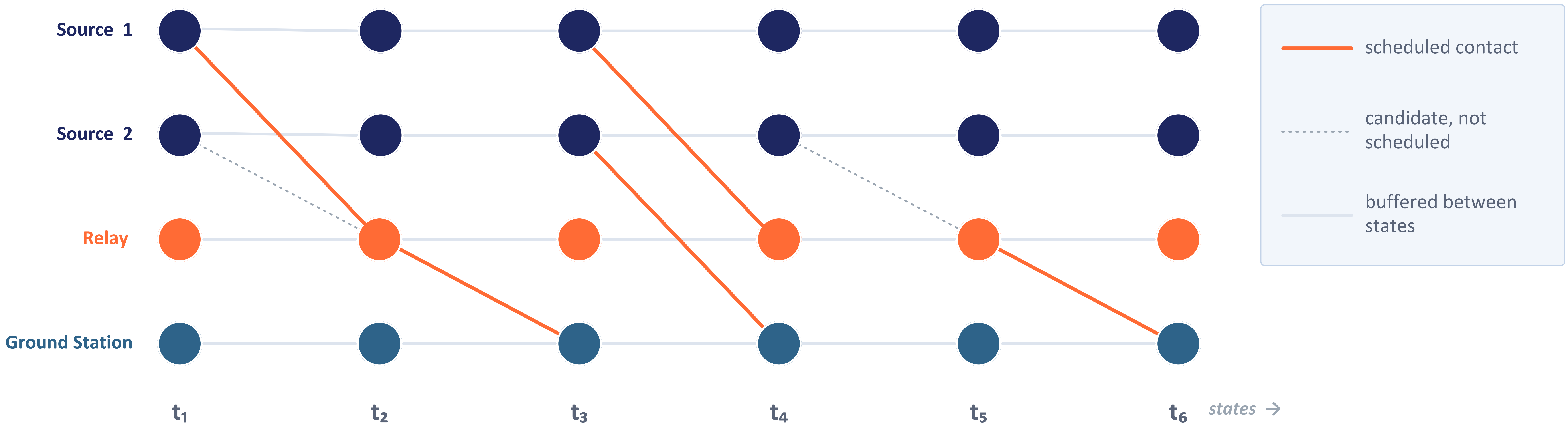
Direct-to-Earth, or Buffer-and-Forward

SCENARIOS

24h,
Increasing the number of source and relay nodes.

Contact plan design on a time-expanded graph

Every state carries its own candidate contact graph — the scheduler only changes how those edges are weighted



BUILD THE GRAPH

Time is discretised into <u>states</u>.
For each state we enumerate every possible link.

WEIGHT THE EDGES

Each scheduler assigns its own <u>weight</u> to every candidate contact.

MATCH AND TRANSMIT

A <u>max-weight maximal matching</u> per state produces the **contact plan**.

Energy models

1. **RTG Power Model**
2. **Energy Consumption Model**
3. **Battery State Model**
4. **Remaining Lifetime Model**

Energy models

1. RTG Power Model
2. **Energy Consumption Model**
3. **Battery State Model**
4. **Remaining Lifetime Model**

1. RTG Power Model

$$P(t) = P_0 \cdot e^{-\lambda t}$$

$$\Rightarrow$$

$$L_m = (1/\lambda)\ \ln(P_0/P_{req})$$

We model New Horizon's GPHS-RTG
(it depletes his power 1.6% per year)

Energy models

1. **RTG Power Model**
2. Energy Consumption Model
3. **Battery State Model**
4. **Remaining Lifetime Model**

2. Energy Consumption Model

$$\left.\begin{aligned} E_{tx} &= P_{avg} \cdot T_{eff} \\ E_{base} &= P_{base} \cdot \Delta t \end{aligned}\right\} \quad E_{total} = E_{tx} + E_{base}$$

E_{base} is all the consumption of other things besides transmission for communications

Energy models

1. **RTG Power Model**
2. **Energy Consumption Model**
3. Battery State Model
4. **Remaining Lifetime Model**

3. Battery State Model

$$E_B^{k+1} = E_B^k + E_{gen} - E_{tx} - E_{base}$$

- Initial state E_B^0
- Restricted values from 0 and E_B^0
- No solar recharge in this model

Energy models

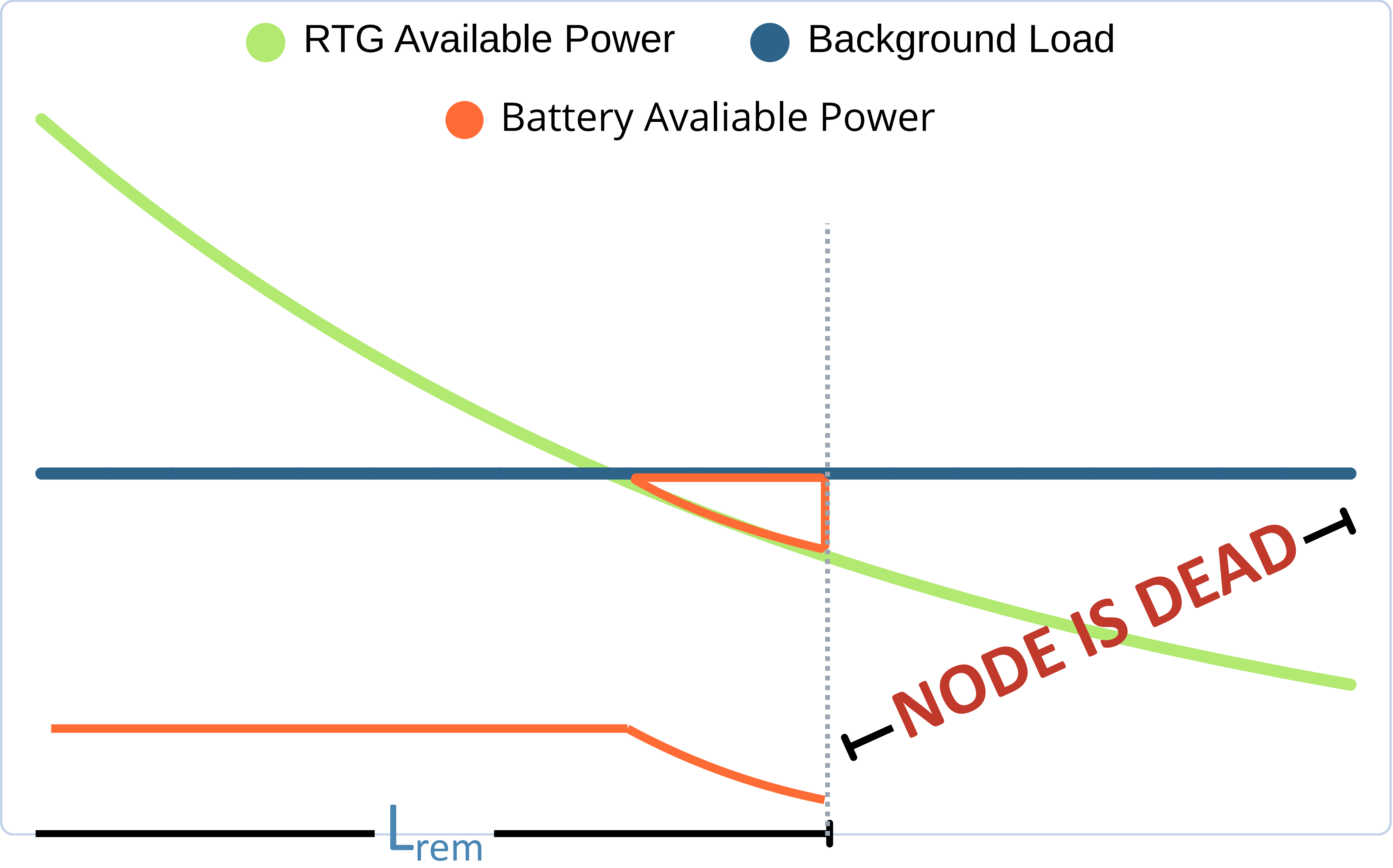
1. **RTG Power Model**
2. **Energy Consumption Model**
3. **Battery State Model**
4. Remaining Lifetime Model

4. Remaining Lifetime Model

$$L_{rem} = \max(0, L_m - t_{current}) + \frac{E_B}{P_{base} + P_{tx}}$$

(time until RTG insufficient + battery buffer time)

When a node is dead?



Schedulers

1. **LLS-Greedy**
2. **Fair Contact Plan (FCP)**
3. **Energy-Aware**
4. **Battery-Aware**
5. **Lifespan-Aware**
6. **DTE Capacity**

All five schedulers work the same way:

- At every step:
  - They build a graph of possible contacts
  - Pick the best set of links that don't overlap.
- The only difference is how they score each link.
- They decide if a link has to be enabled/used or not.

Schedulers

Two baselines, three of ours, one reference bound — same machinery, different edge weight

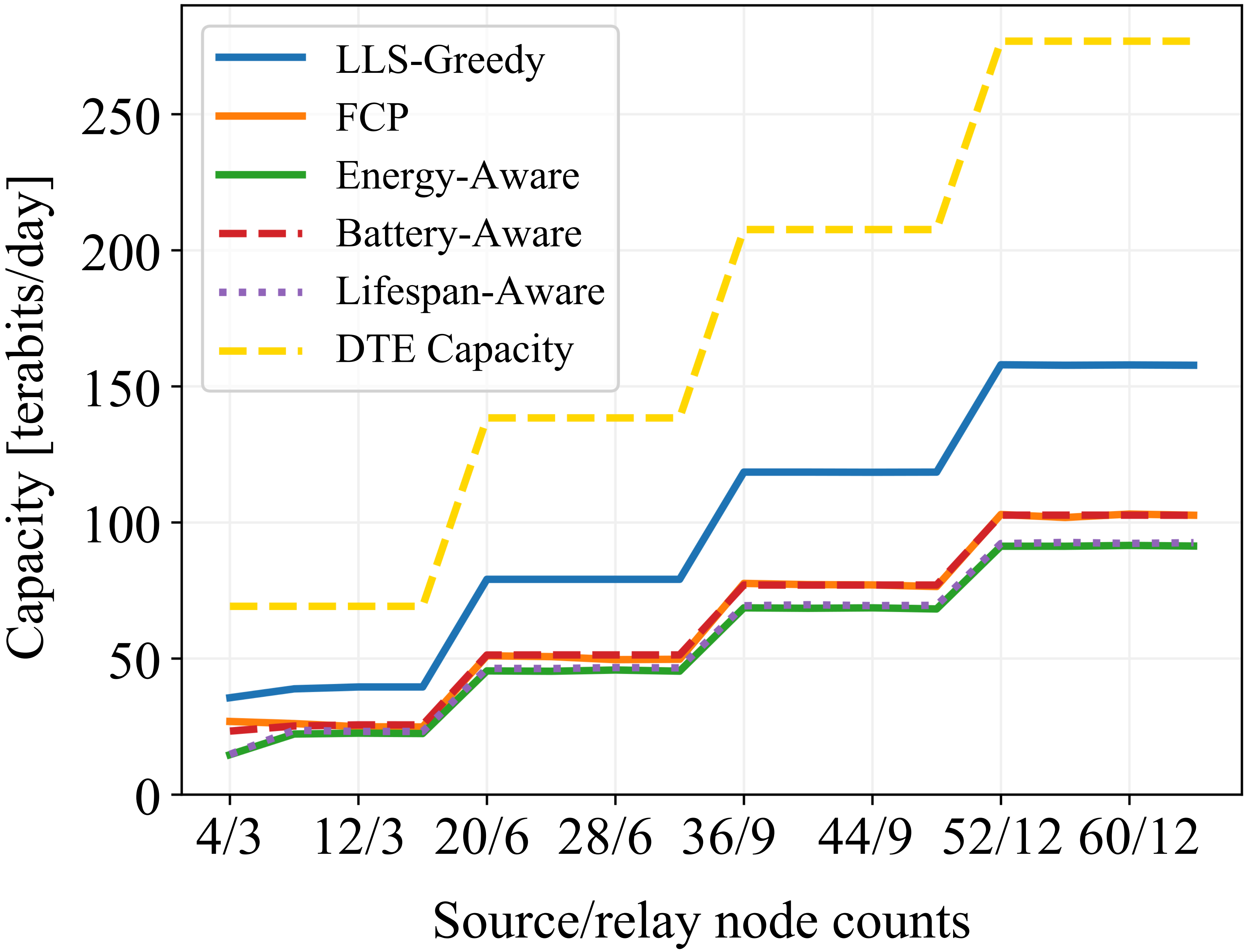
Scheduler	Edge weight	Memory	Scope
LLS-Greedy (baseline)	ΔC — the gain in data actually delivered to Earth	in the flow model	**END-TO-END**
FCP (baseline)	time since the node's last contact	—	**local**
Energy-Aware (ours)	RTG energy generated − transmit energy, this state	—	**local**
Battery-Aware (ours)	projected battery level after generation and draw	**yes**	**local**
Lifespan-Aware (ours)	remaining lifetime — RTG headroom + battery buffer, minimum across the link's two nodes	**yes**	**local**
DTE Capacity	*not a scheduler — upper bound if only direct-to-Earth links are used*	—	—

Look at the last column. LLS-Greedy asks whether the data gets home.
The other four only ask whether the node can afford the contact.

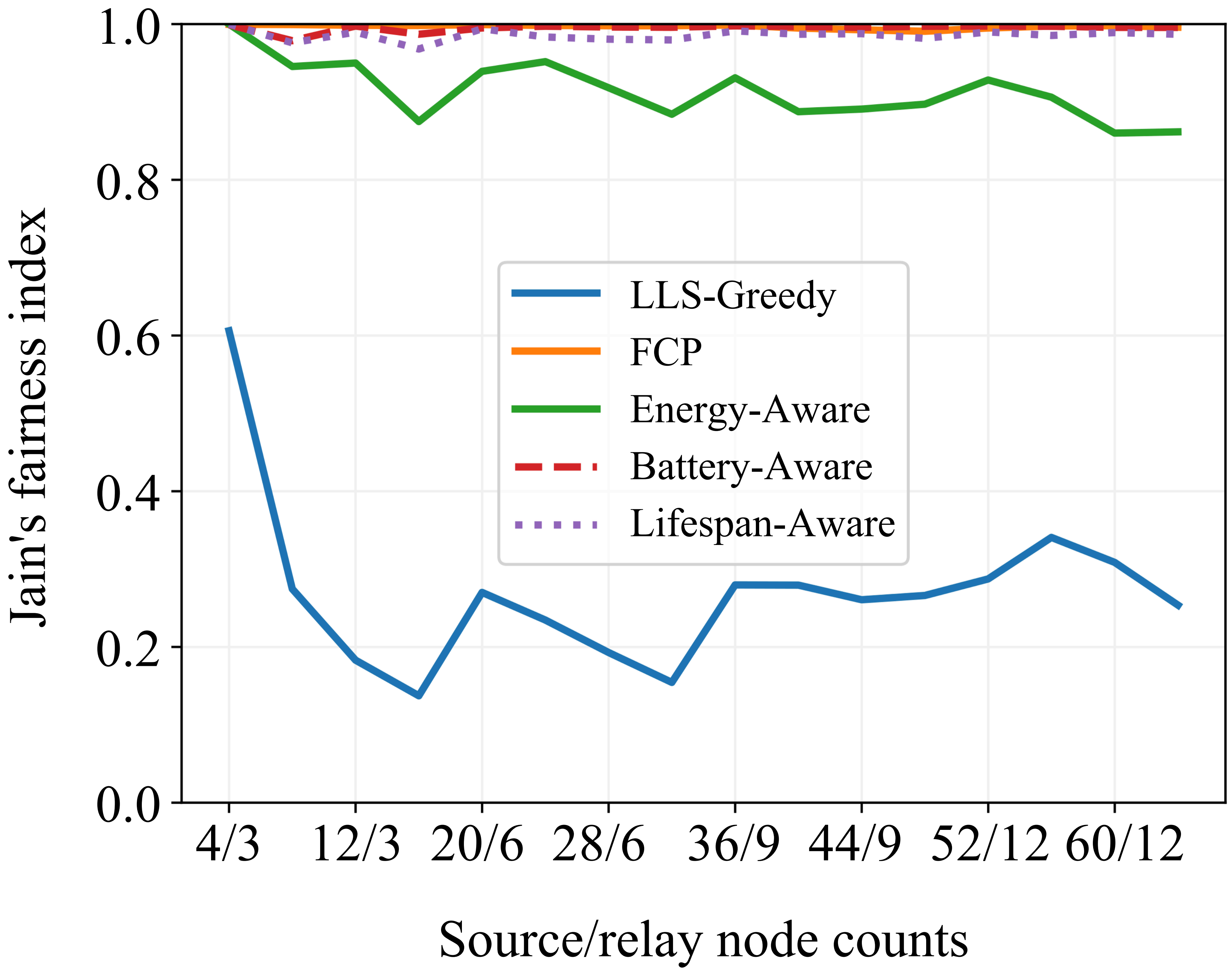
Simulation settings

Average transmit power P_{avg}	4W
Power baseline for basic operations P_{base}	64W
Source node bitrate	267 Mbps (33 million km away)
Relay node bitrate	267 Mbps (33 million km away)
Ground-station bitrate	1.2 Gbps
Lasers per node	1
Scenario horizon	24h
RTG initial power	70W
RTG decay constant (λ)	1.6% per year

Network Capacity

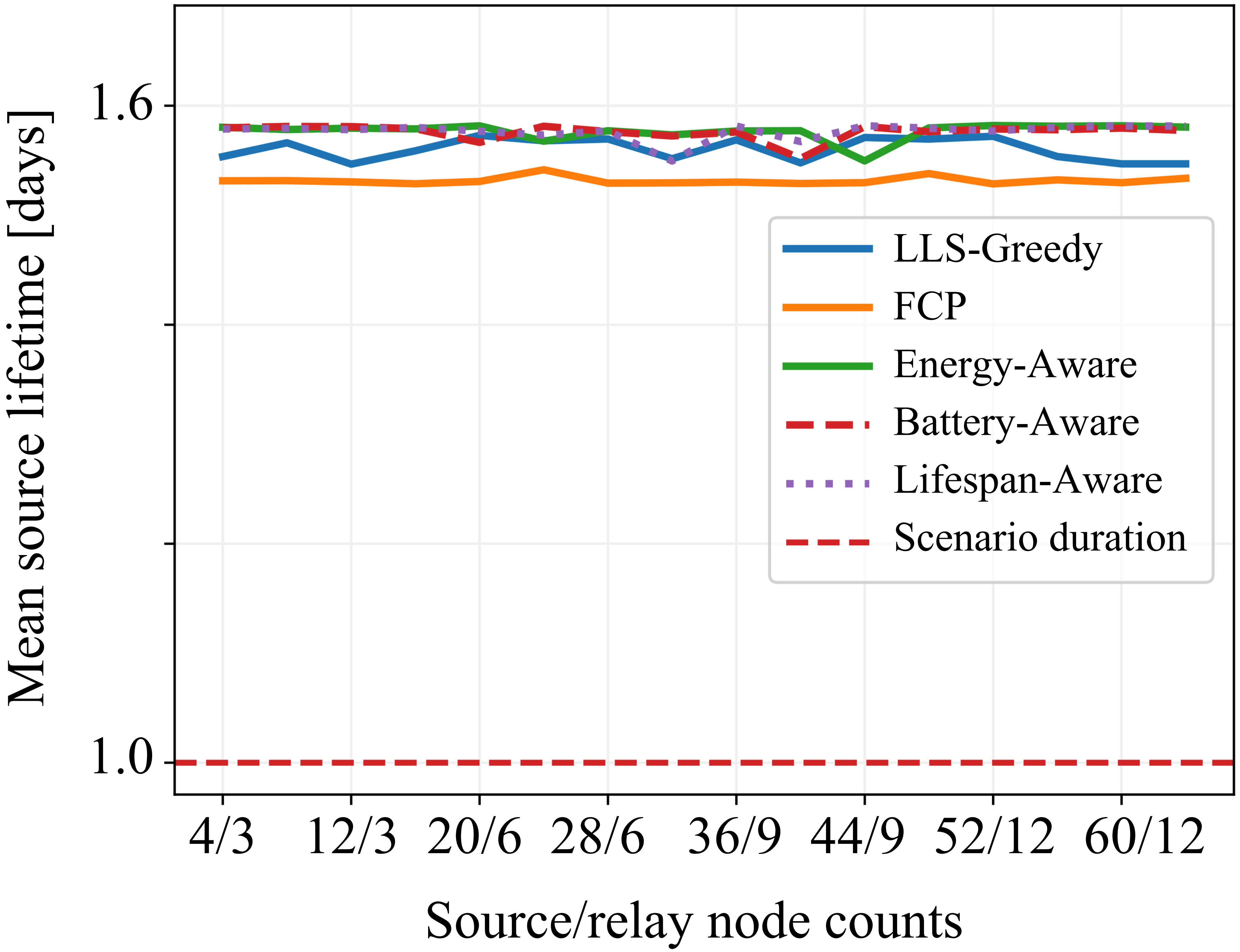


Fairness

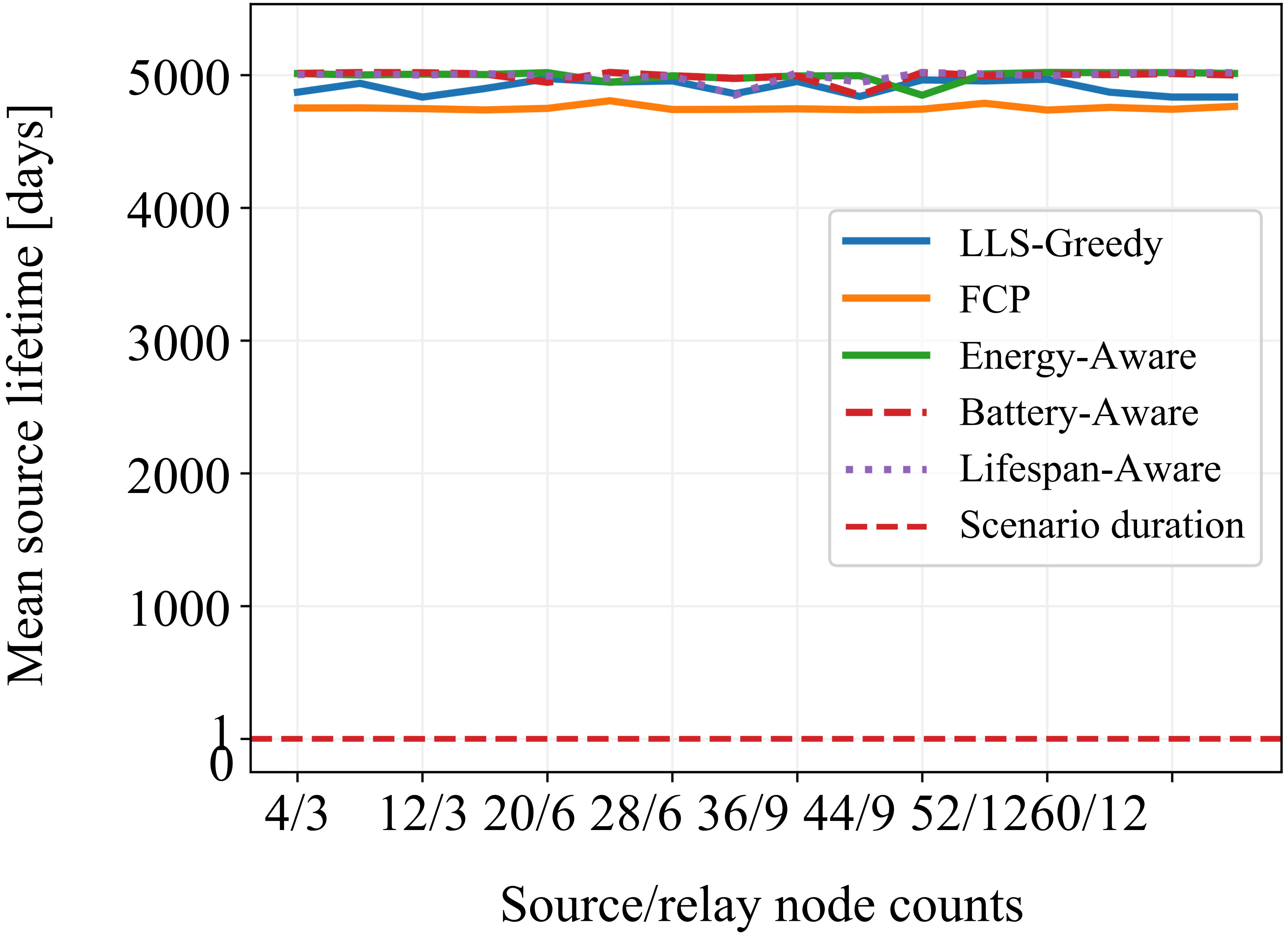


1.0
0.8
0.6
0.4
0.2
0.0
Jain's fairness index
4/3
12/3
20/6
28/6
36/9
44/9
52/12
60/12
Source/relay node counts
LLS-Greedy
FCP
Energy-Aware
Battery-Aware
Lifespan-Aware

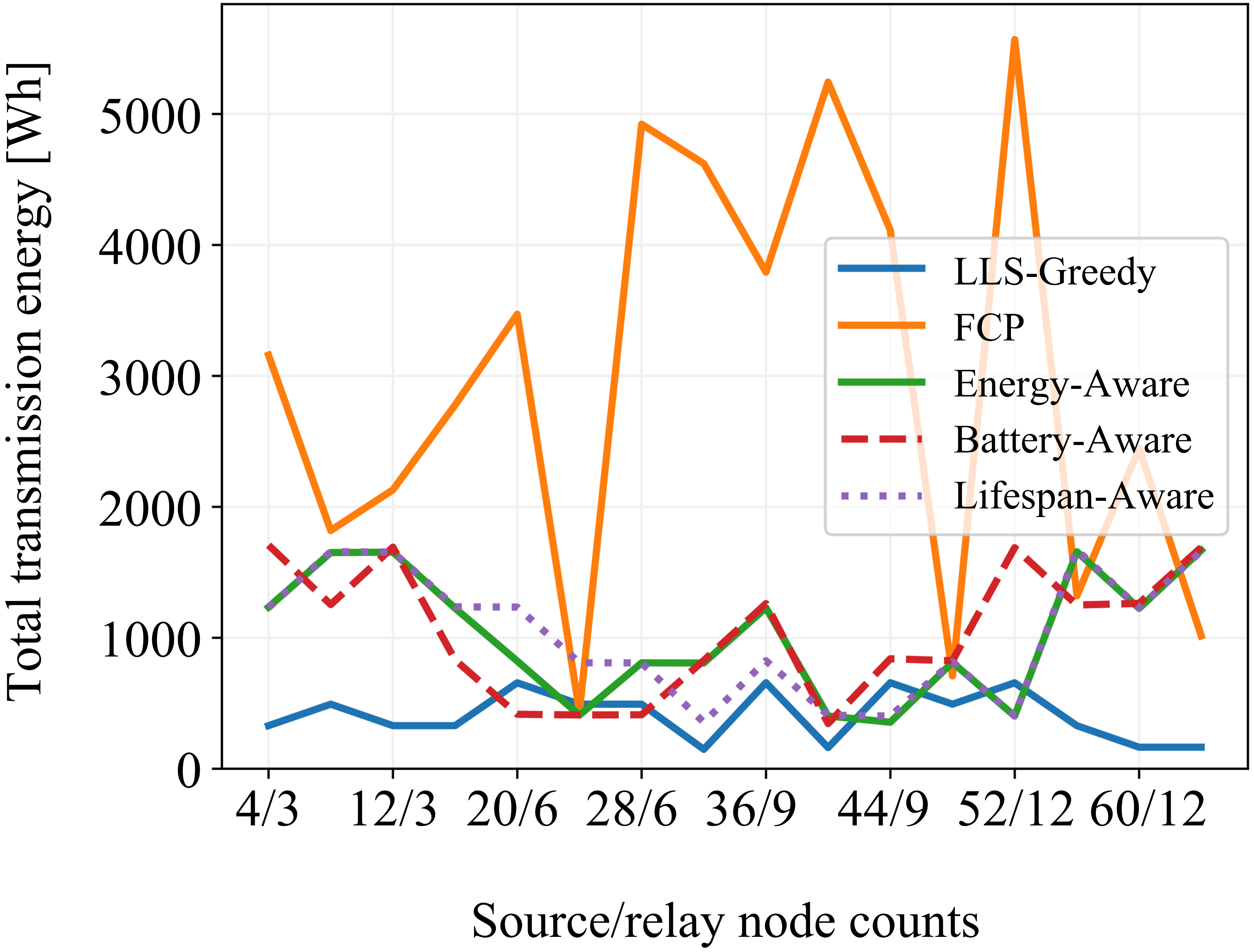
Mean Source Lifetime



Mean Source Lifetime



Total TX Energy

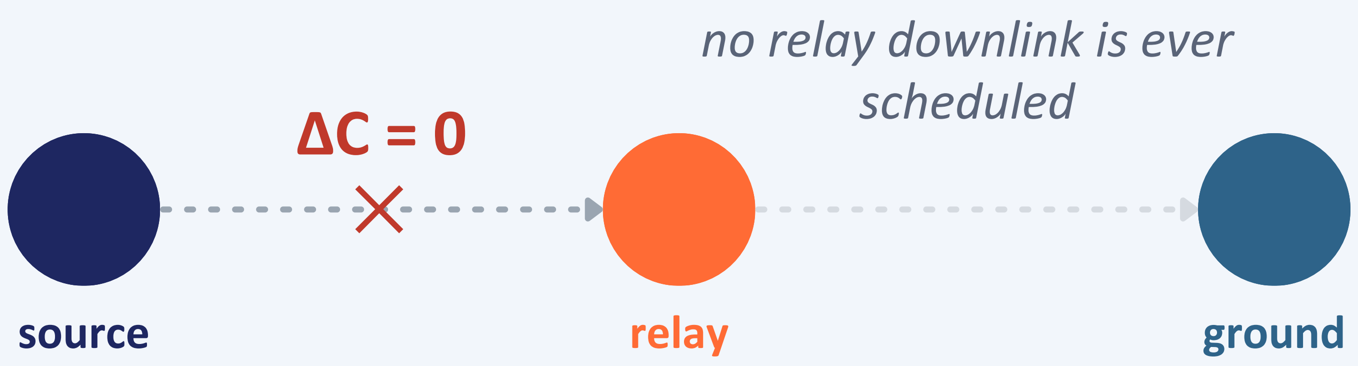


The effect of ΔC = 0

MISSION

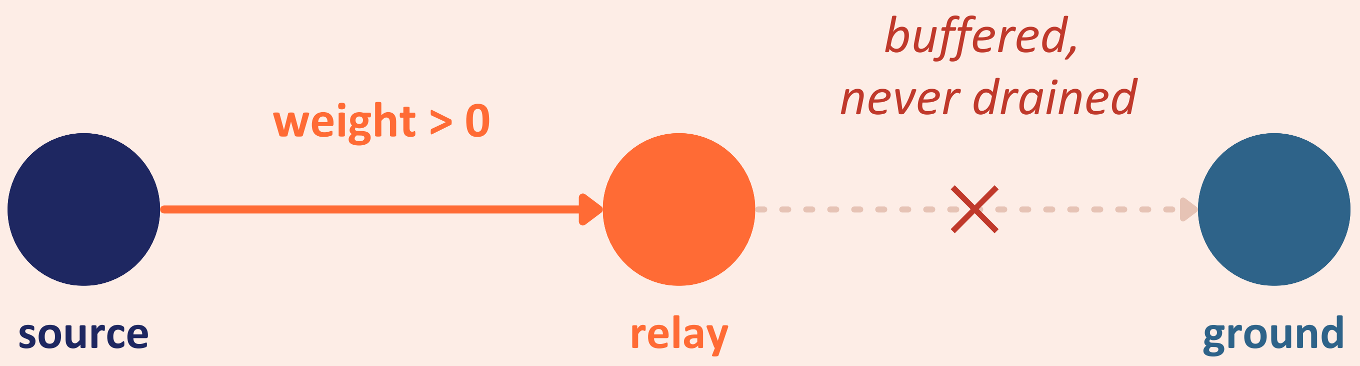
UNC Universidad Nacional de Córdoba

LLS-Greedy — end-to-end weight



The matching leaves the contact unscheduled.
Not an explicit filter an emergent property of the max-flow model.

Resource-aware — local weight



The weight cannot see downstream.
The contact passes the energy check, so the edge is accepted and the energy is spent.

Not a fairness rule, not an energy rule — relay protection is emergent from scoring contacts end-to-end.

LLS-Greedy keeps relays idle only by routing everything DTE,
which loads its sources as heavily as everyone else and sources are what bound network lifetime.

Take aways

MISSION | UNC Universidad Nacional de Córdoba

Weighting contacts by energy or lifetime, without an end-to-end delivery model, is counterproductive.

The scheduler spends scarce power on data that never reaches its destination.

A two-stage weight: Capacity decides IF, resources decide WHICH

Candidate contact

every feasible link in the state

→

ΔC > 0 ?

does this contact increase delivered end-to-end capacity at all?

→

RANK: lifespan weight

break ties between equally productive contacts on energy, battery, lifetime

→

Schedule

throughput preserved, resources respected

if ΔC = 0 the contact is discarded regardless of how healthy the nodes look

FUTURE WORK

Implement and evaluate the two-stage weight. And find new variants for the convination of capacity and lifetime.

Thanks! 😁

https://github.com/jason-gerard/laser-link-scheduler/tree/lifespan-aware-scheduling

References:

- **FCP**: J. A. Fraire, P. G. Madoery, and J. M. Finochietto, "On the design and analysis of fair contact plans in predictable delay-tolerant networks," IEEE Sensors Journal, vol. 14, no. 11, pp. 3874–3882, Nov. 2014.
- **LLS-Greedy**: J. Gerard, A. Ibrahim, J. A. Fraire et al., "Autonomous max-flow interplanetary laser link scheduling for martian exploration," in 2024 IEEE WiSEE. IEEE, Dec. 2024, pp. 70–75.
- **RTG:** https://ntrs.nasa.gov/api/citations/20160001769/downloads/20160001769.pdf
- **RTG decay / GPHS-RTG (New Horizons-class):** R. M. Ambrosi, H. Williams, E. J. Watkinson et al., "European radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs) for space science and exploration," Space Science Reviews, vol. 215, no. 8, p. 55, 2019.
- **Battery-aware CPD**: J. A. Fraire, G. Nies, C. Gerstacker et al., "Battery-aware contact plan design for LEO satellite constellations: The Ulloriaq case study," IEEE Transactions on Green Communications and Networking, vol. 4, no. 1, pp. 236–245, Mar. 2020.
- **75% of Mars Relay Network data dropped**: R. Gladden, E. Pereira, and B. Sauer, "Lessons learned from the mars relay network: Considerations for future relay networks," in 2024 IEEE Aerospace Conference, 03 2024, pp. 1–16.
- **PAT process**: D. Bhattacharjee, P. G. Madoery, A. U. Chaudhry et al., "On-demand routing in LEO mega-constellations with dynamic laser inter-satellite links," IEEE Transactions on Aerospace and Electronic Systems, vol. 60, no. 5, pp. 7089–7105, 2024.
- **Retargeting / PAT delay model**: J. Gerard, J. A. Fraire, and S. Céspedes, "Modeling pointing, acquisition, and tracking delays in free-space optical satellite networks," in 2025 IEEE WiSEE. IEEE, 2025, pp. 1–6.
- **FSO capacity and SWaP-C advantage**: G. Wang, F. Yang, J. Song et al., "Free space optical communication for inter-satellite link: Architecture, potentials and trends," IEEE Communications Magazine, vol. 62, no. 3, pp. 110–116, 03 2024.
- **DSN autonomy limits / optical CPD**: J. Gerard, J. A. Fraire, and S. Céspedes, "Contact plan design for optical interplanetary communications," 01 2026.
- **DSOC-class terminal (4 W avg TX power, 267 Mbps, 16-PPM):** A. Biswas, M. Srinivasan, K. Andrews et al., "Deep space optical communications technology demonstration," in Free-Space Laser Communications XXXVI, vol. 12877. SPIE, 2024, pp. 32–43.
- **One laser per spacecraft (SWaP-C constraint)**: M. D. Soria-Santacruz, H. A. Bates-Tarasewicz, W. S. Chhit et al., "Systems engineering of the Psyche payload," in 2024 IEEE Aerospace Conference, 2024, pp. 1–24.
- **Optical ground stations / adaptive optics (LCOT)**: R. E. Lafon, Y. Bai, A. Caroglanian et al., "Current status of NASA's low-cost optical terminal (LCOT) at Goddard Space Flight Center," in Free-Space Laser Communications XXXV, vol. 12413. SPIE, 2023.
- **DSN site locations:** B. Edwards, D. Antsos, A. Biswas et al., "Addressing the high-rate deep space communications shortfall in NASA's space technology mission directorate's envisioned future," in 29th Ka and Broadband Communications Conference, Seattle, WA, 2024.
- **Dual-terminal relay (LCRD) / battery and power parameters:** D. J. Israel, B. L. Edwards, R. L. Butler et al., "Early results from NASA's laser communications relay demonstration (LCRD) experiment program," in Free-Space Laser Communications XXXV, vol. 12413. SPIE, 2023, pp. 10–24.
- **Buffer-and-burst downlink (TBIRD)**: K. Riesing, C. Schieler, B. Bilyeu et al., "Operations and results from the 200 Gbps TBIRD laser communication mission," in 37th Annual Small Satellite Conference, Logan, UT, 2023.
- **IPN relay architectures (LunaNet):** D. J. Israel, K. D. Mauldin, C. J. Roberts et al., "LunaNet: A flexible and extensible lunar exploration communications and navigation infrastructure," in 2020 IEEE Aerospace Conference, 2020, pp. 1–14.
- **Data-producing IPN constellations:** O. Ledesma, P. Lamo, J. Fraire et al., "Architectural framework and feasibility of internet of things-driven mars exploration via satellite constellations," Electronics, vol. 13, p. 1289, 01 2024.
- **Contact plan generation / visualization (IPN-V):** A. Le Bihan, J. A. Fraire, P. Francois et al., "IPN-V: The interplanetary network visualizer," in 2024 IEEE SMC-IT, 2024, pp. 142–150. — https://gitlab.inria.fr/jfraire/ipn-v
- **Orbit generation tool**: https://github.com/jason-gerard/orbit-generator
- **Implementation (this work):** https://github.com/jason-gerard/laser-link-scheduler/tree/lifespan-aware-scheduling