IR-CGR: Time-Aware Inter-Region Contact Graph Routing for Scalable Space DTNs

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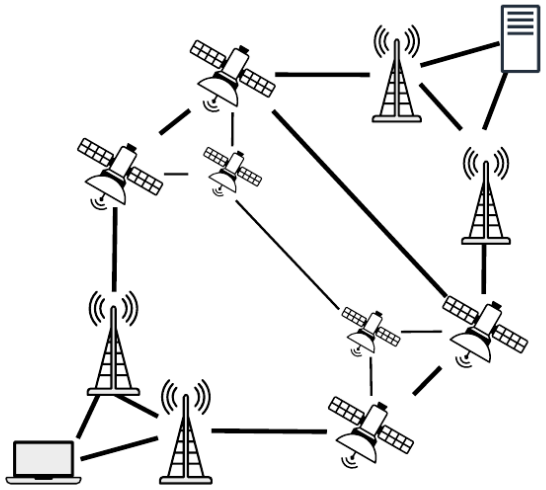
Outline

1. **Background and existing methods**
   CGR has a scalability problem; LRK loses timing information.
2. **Proposal: IR-CGR**
   A time-aware inter-region routing method.
3. **Evaluation Setup**
   Two benchmarks for robustness and scalability.
4. **Orbital Benchmark**
   Delivery robustness in a realistic lunar scenario.
5. **Scaling Benchmark**
   Computational scaling with network size.
6. **Summary**
   Benefits and trade-offs of IR-CGR.

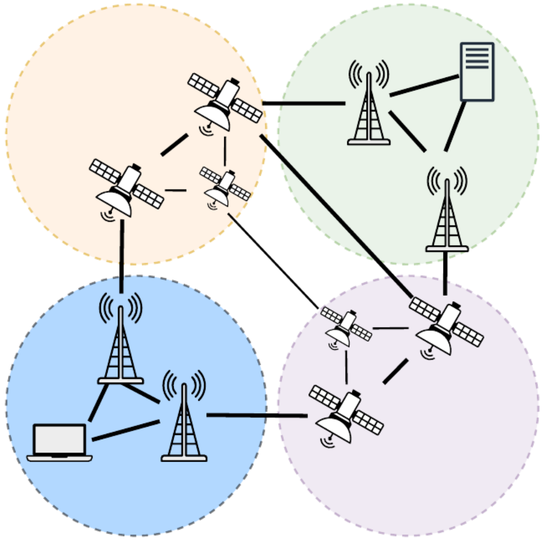
Background: the CGR scalability problem

CHALLENGE

- DTN protocols are being standardized and adopted for future space networking.
- CGR exploits predicted future contacts to compute routes in scheduled DTNs.
- Its worst-case route-search complexity is $O(|C|^2)$ (※ |C| = number of contacts)



Space Network **without** regions:
every node searches the full plan

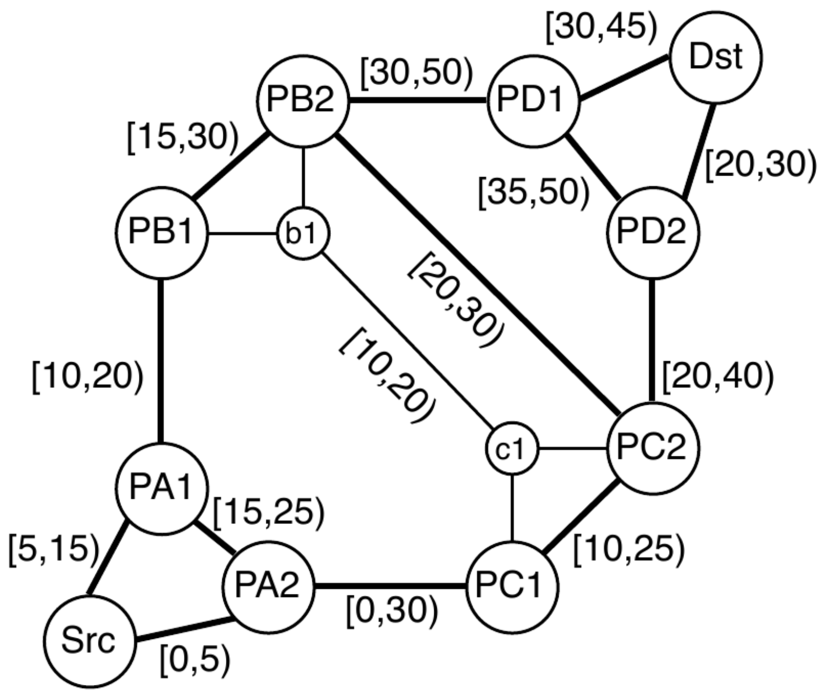


Space Network **with** regions:
each node searches its region

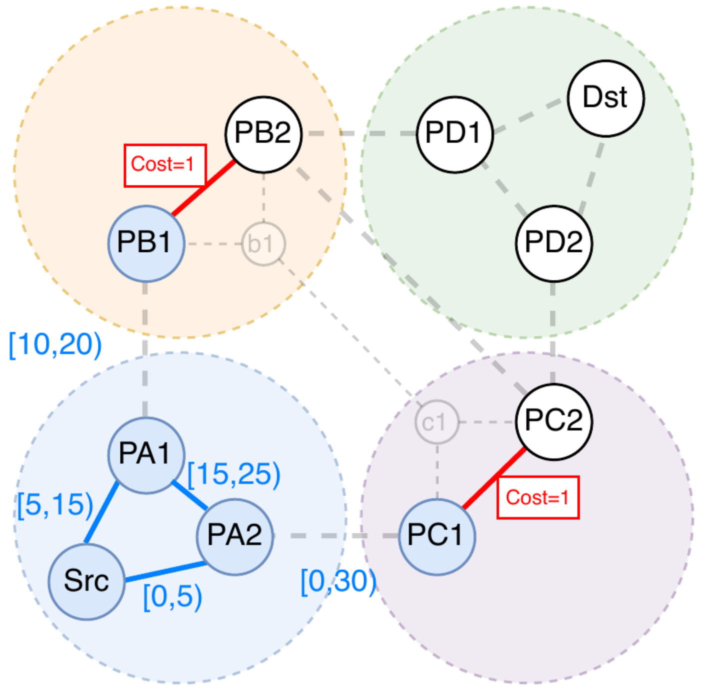
Contact plans grow with network size, while onboard resources do not.
➡ Each node's knowledge of the network must be bounded.

Existing method: Local Regionalized Knowledge (LRK) [2]

Global Full Knowledge (GFK)
(= Conventional CGR without Region)



Local Regionalized Knowledge (LRK)



Intra-region

- Regional CGR on the regional contact plan
- Contact windows preserved → **time-aware**

Inter-region

- Static passageway graph with fixed crossing costs
- Contact windows not represented → **time-static**

LRK keeps each node's routing knowledge small.
But can it work well when timing information is lost at region crossings?

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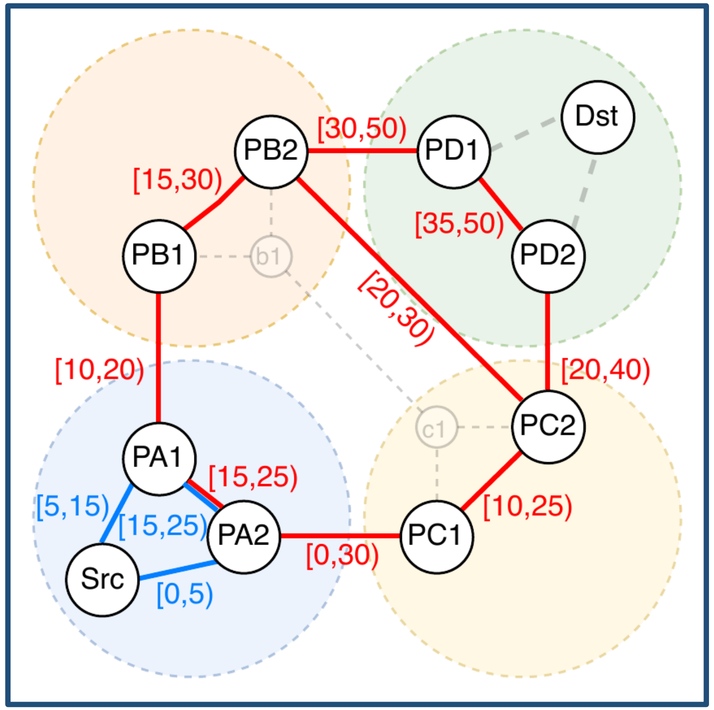
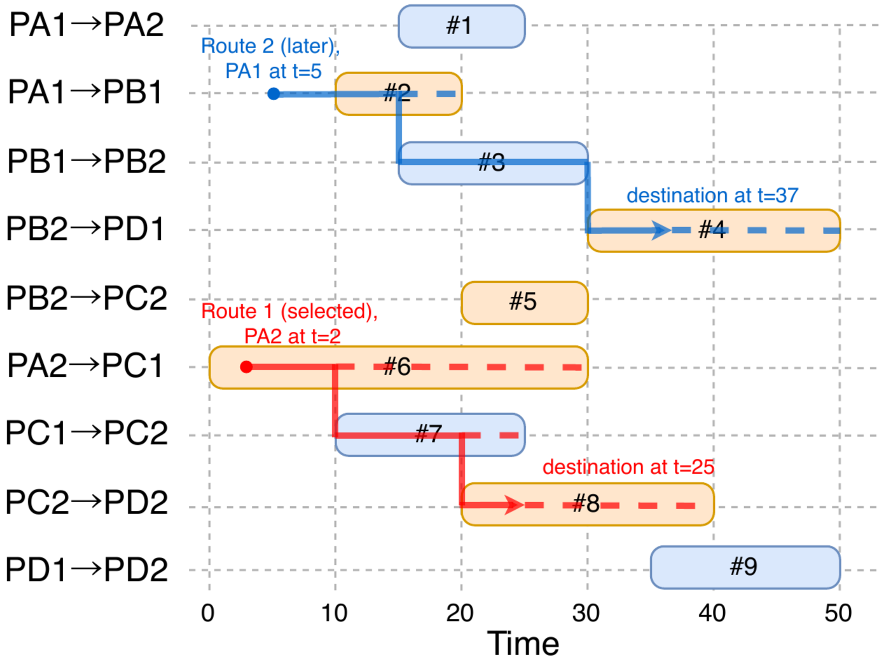
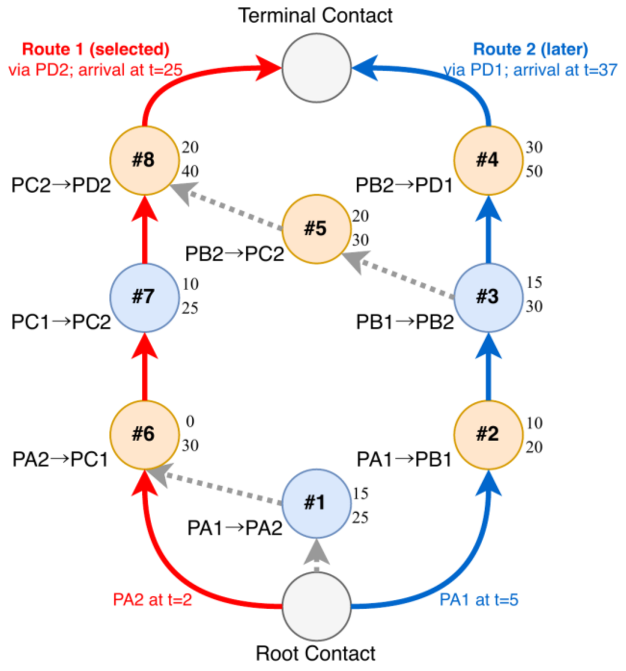
Proposal: Inter-Region Contact Graph Routing (IR-CGR)



Divide network into regions



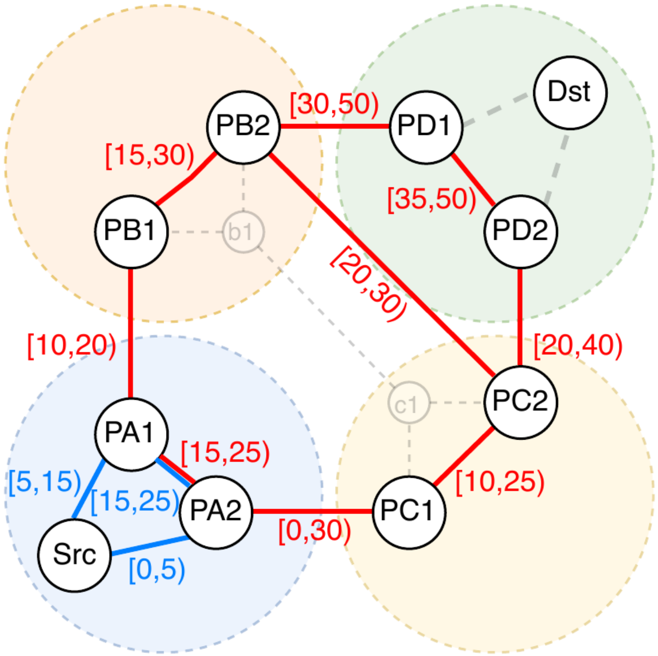
IR-Contact Plan (IRCP)



IR-Dijkstra

- Same regionalization as LRK
- But inter-region crossings keep their contact windows

Proposal: Inter-Region Contact Graph Routing (IR-CGR)



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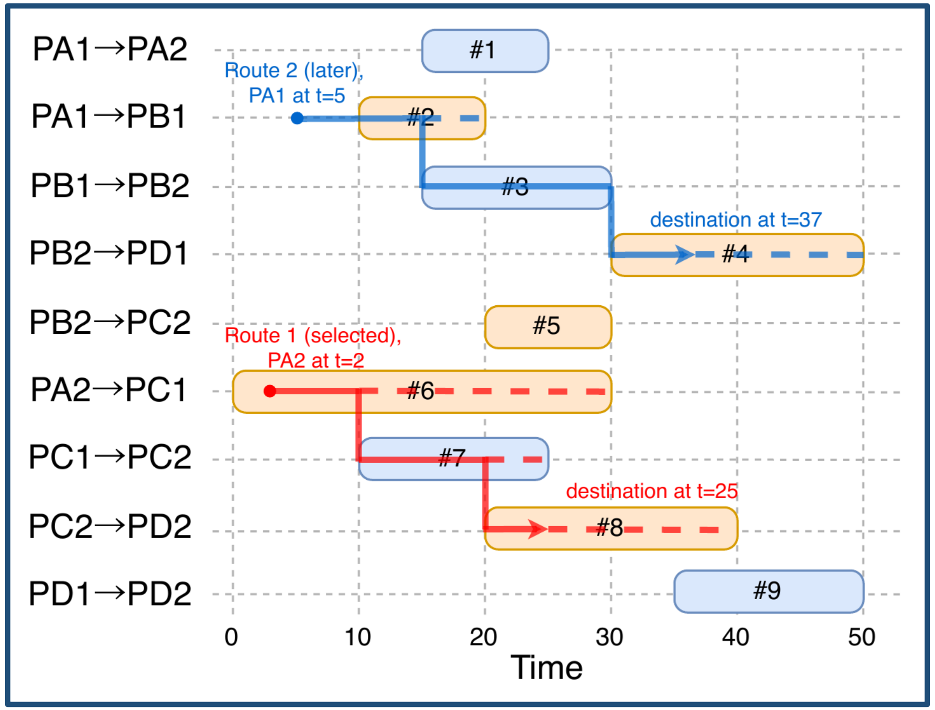
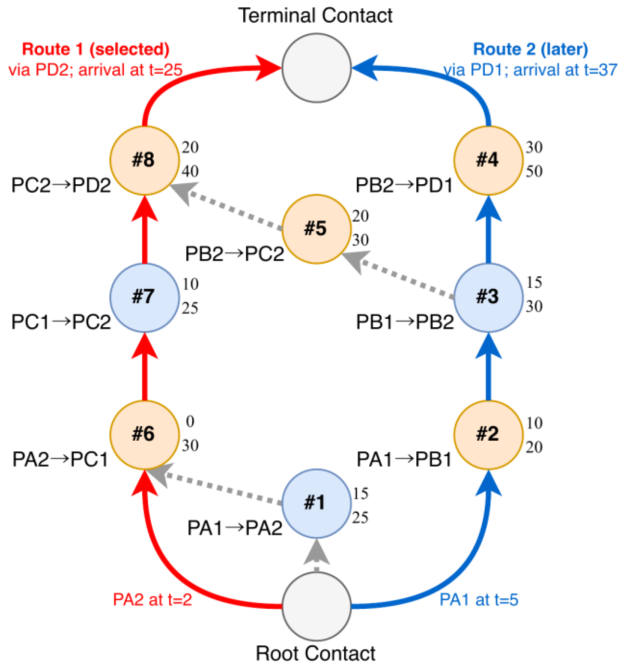


IR-Contact Plan (IRCP)

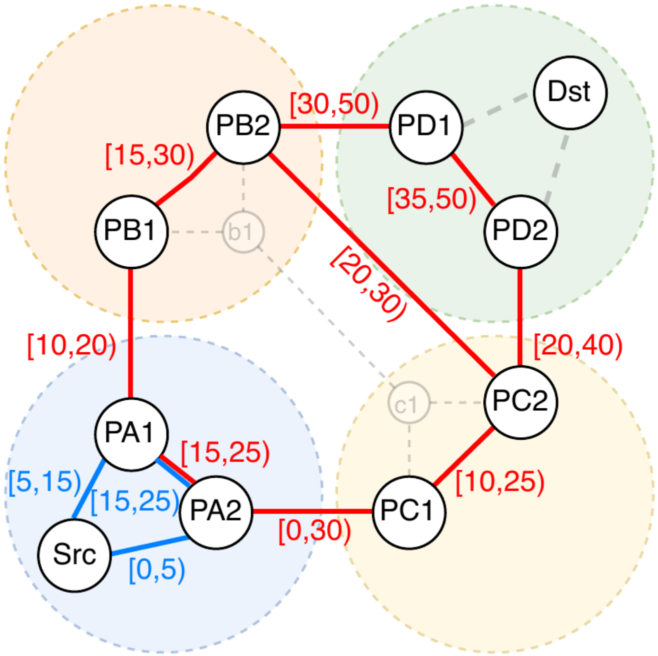


IR-Dijkstra

- **INTER IR-Contact** : actual cross-region contacts
- **INTRA IR-Contact** : sampled passageway-to-passageway transit
- IRCP is built on the ground for each planning horizon

※Planning horizon = the time span covered by the contact plan

Proposal: Inter-Region Contact Graph Routing (IR-CGR)



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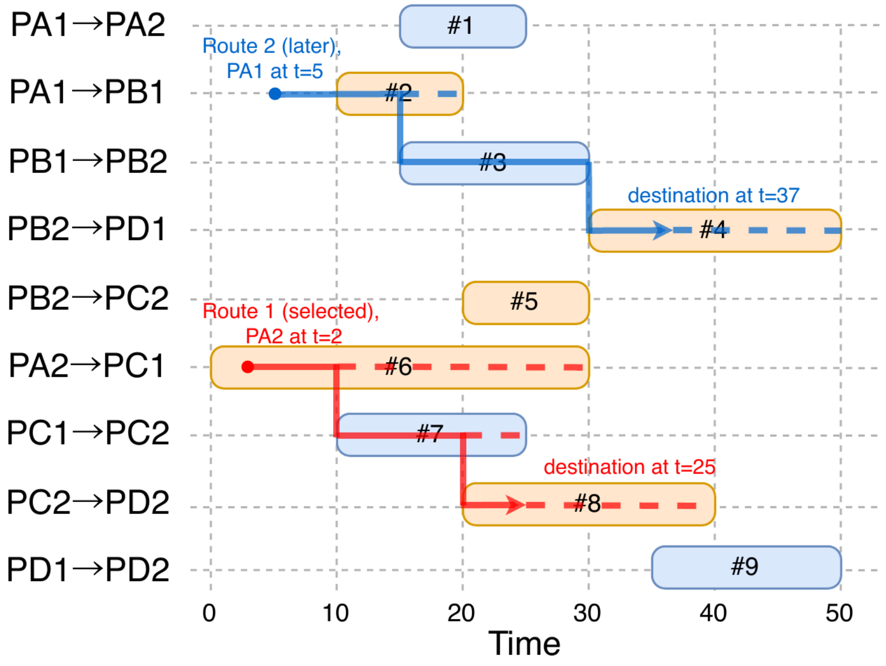
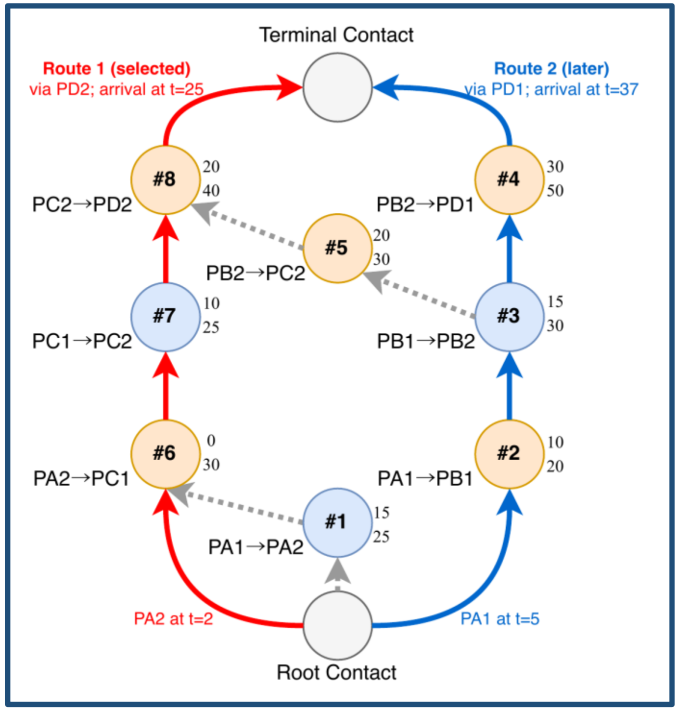


IR-Contact Plan (IRCP)



IR-Dijkstra

- IR-Dijkstra searches the IRCP for the earliest-arrival passageway sequence
- Regional CGR forwards the bundle to the next passageway

Same time-aware routing idea as CGR, applied one level higher.

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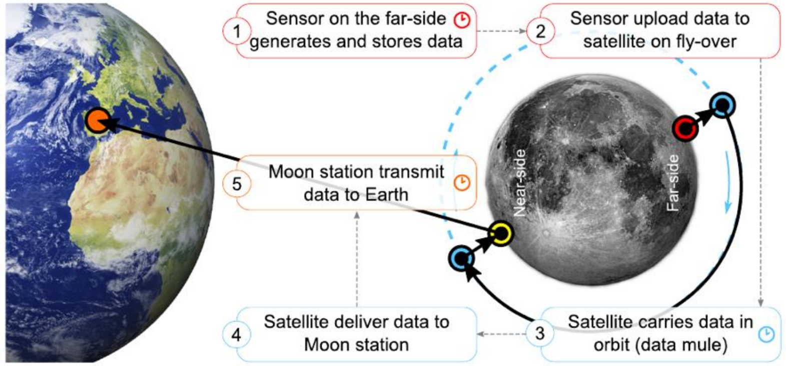
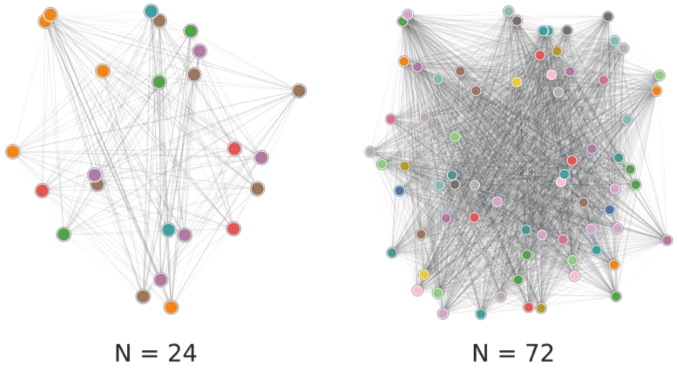
Evaluation setup



Lunar Ring Road concept, Feldmann et al. [3], © 2018 IEEE



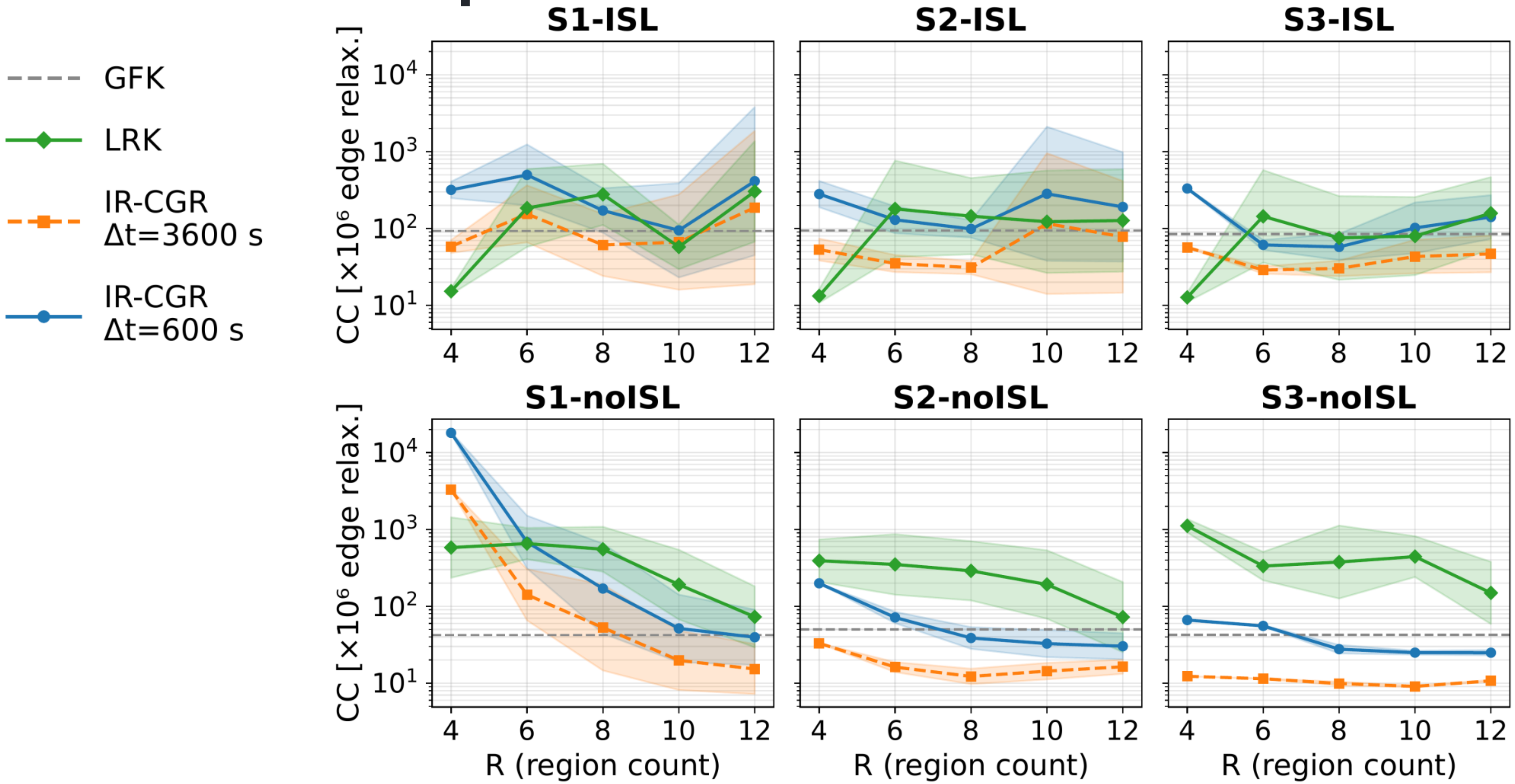
Synthetic contact plans, varying size and contact regime

	Orbital Benchmark (Lunar Ring Road [3])	Scaling Benchmark (DDRCM)
Network	23 nodes, orbital contact plan	24 to 72 nodes, synthetic plan
Links	with/without inter-satellite links (ISLs) between lunar satellites	three distance-dependent contact regimes (β = 1, 2, 4)
Sweep	4 to 12 regions	4, 8 or 12 nodes per region
Seeds	100	20
Compared / metrics	GFK, LRK, IR-CGR; delivery ratio, delay, cost	

Orbital Benchmark: Evaluates delivery robustness in a realistic orbital scenario
Scaling Benchmark: Evaluates computational scaling with network size

Outline

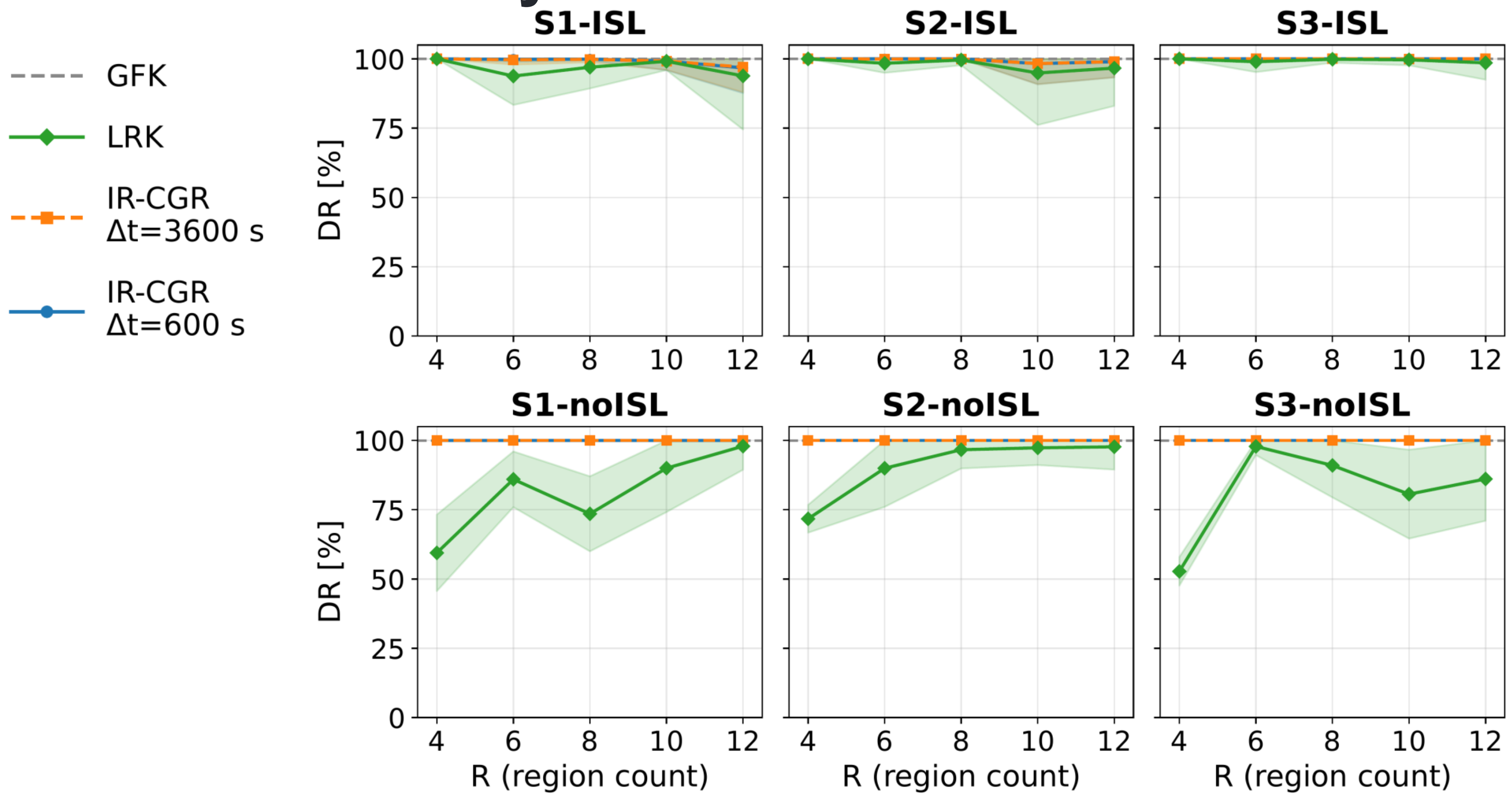
Orbital Benchmark: Computational Cost



- **With coarse partitioning, both IR-CGR and LRK can cost more than GFK.**
- **With suitable partitioning, IR-CGR can cost less than both GFK and LRK.**

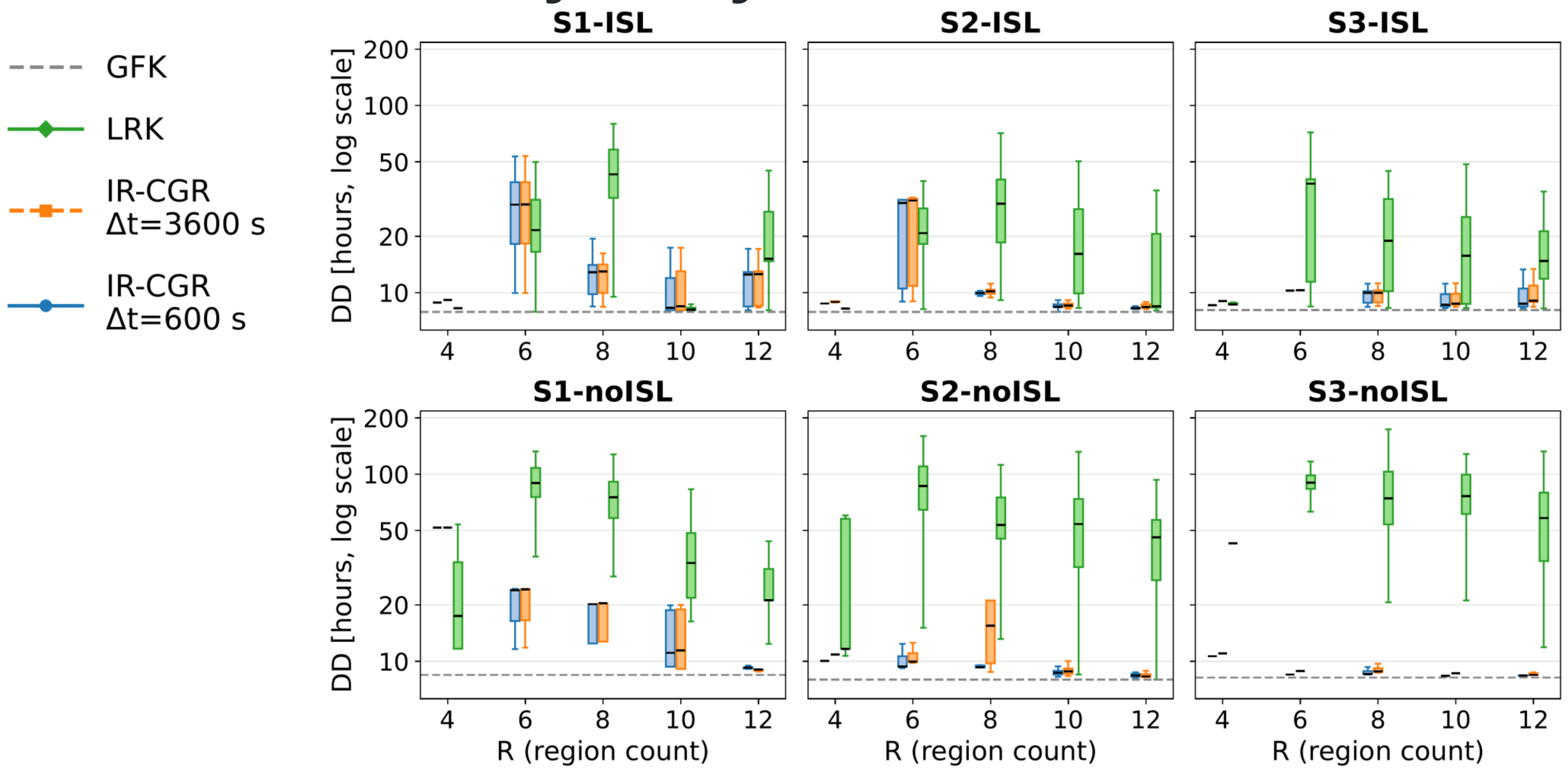
→ The operator's partitioning choice therefore determines the routing-cost trade-off.

Orbital Benchmark: Delivery Ratio



- **LRK loses delivery when inter-region connectivity becomes sparse**
- **IR-CGR (Δt=3600 s) maintains full delivery across the evaluated no-ISL cases.**

Orbital Benchmark: Delivery Delay

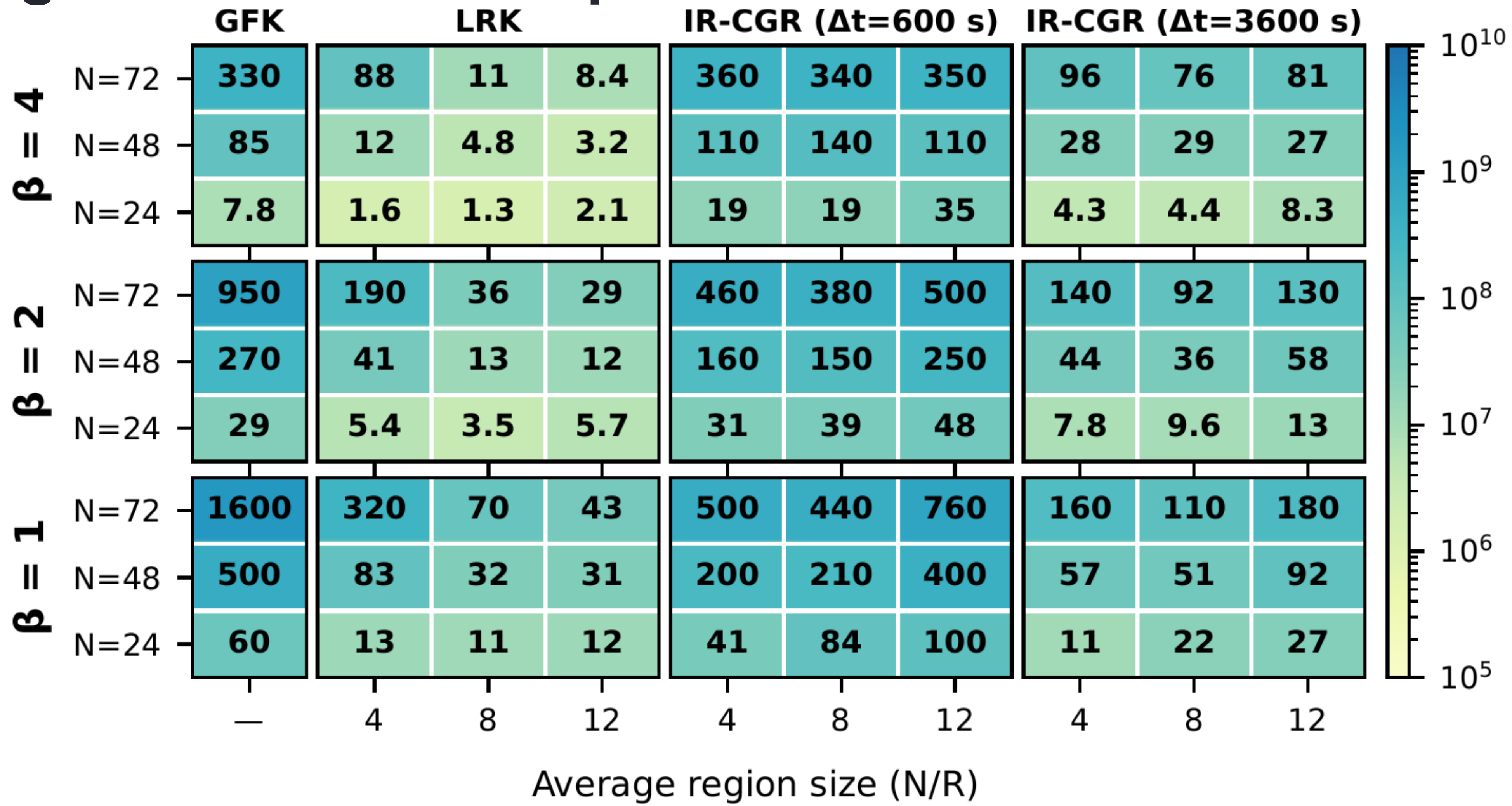


- **With suitable partitioning, IR-CGR stays close to GFK; coarse partitions can increase its delay.**
- **LRK shows much larger and more variable delays, especially without ISLs.**

Outline

Scaling Benchmark: Computational Cost

Every design delivers every bundle on this grid.
Cell = 20-seed mean; CC = edge relaxations



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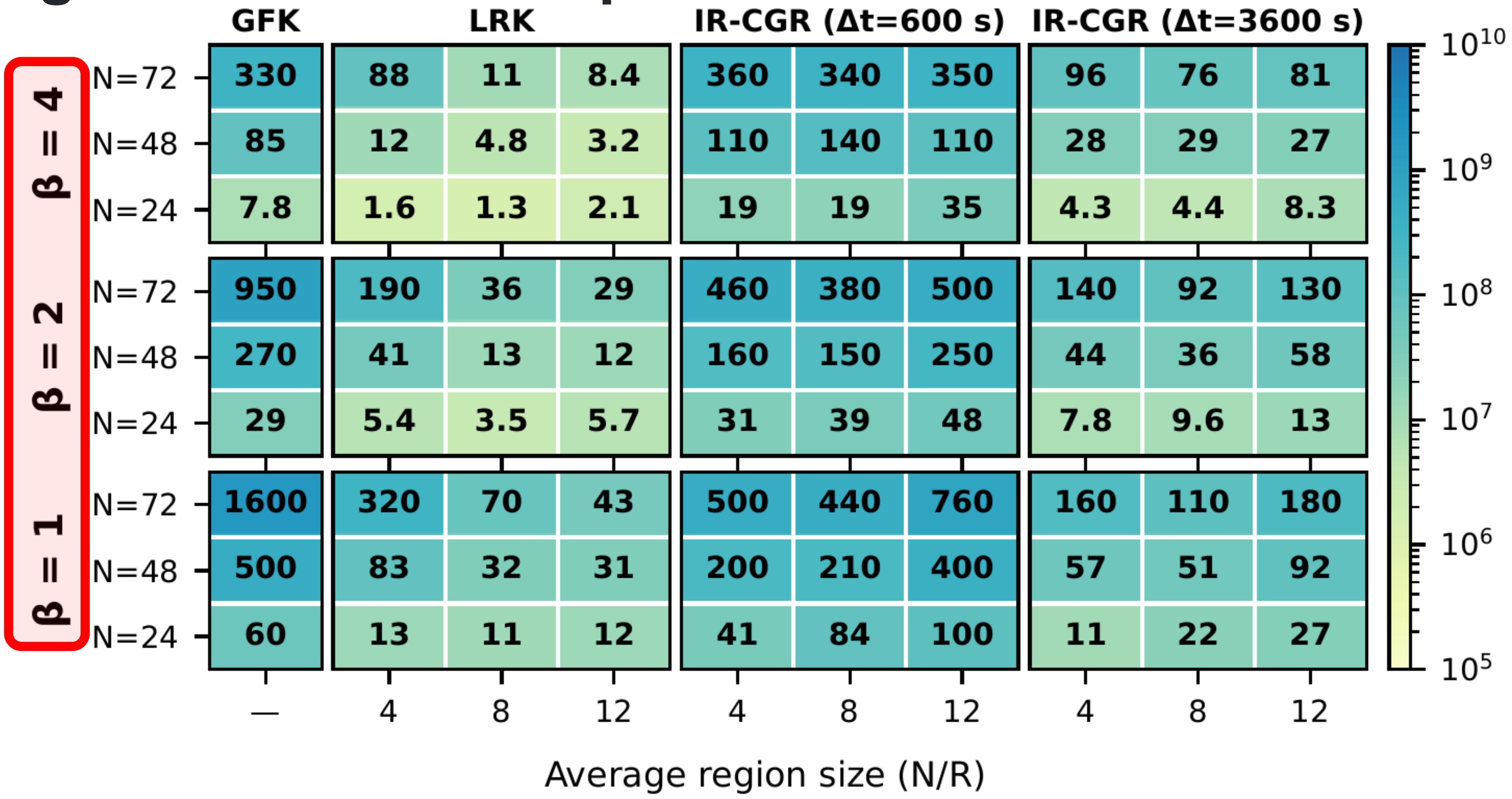

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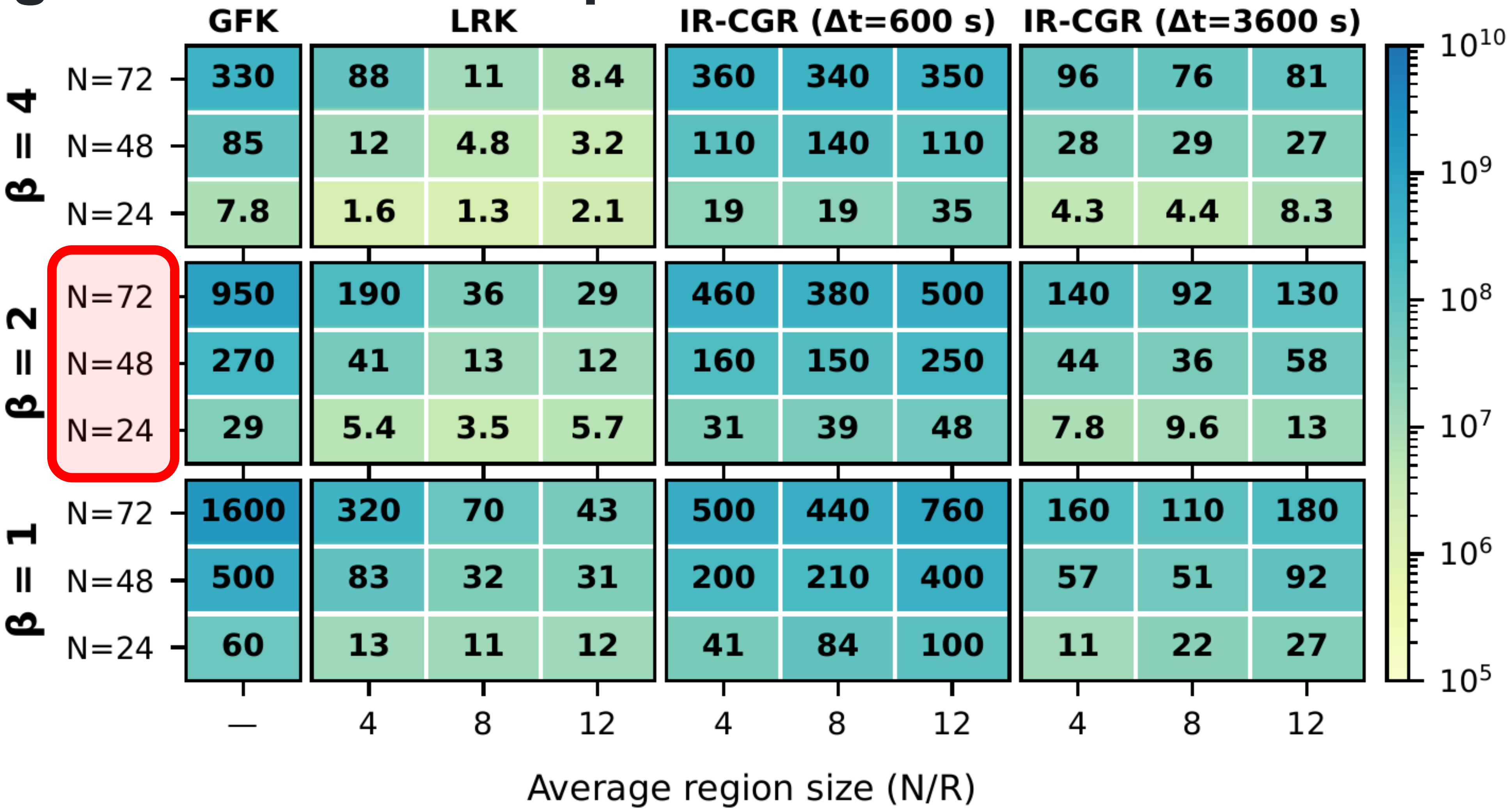

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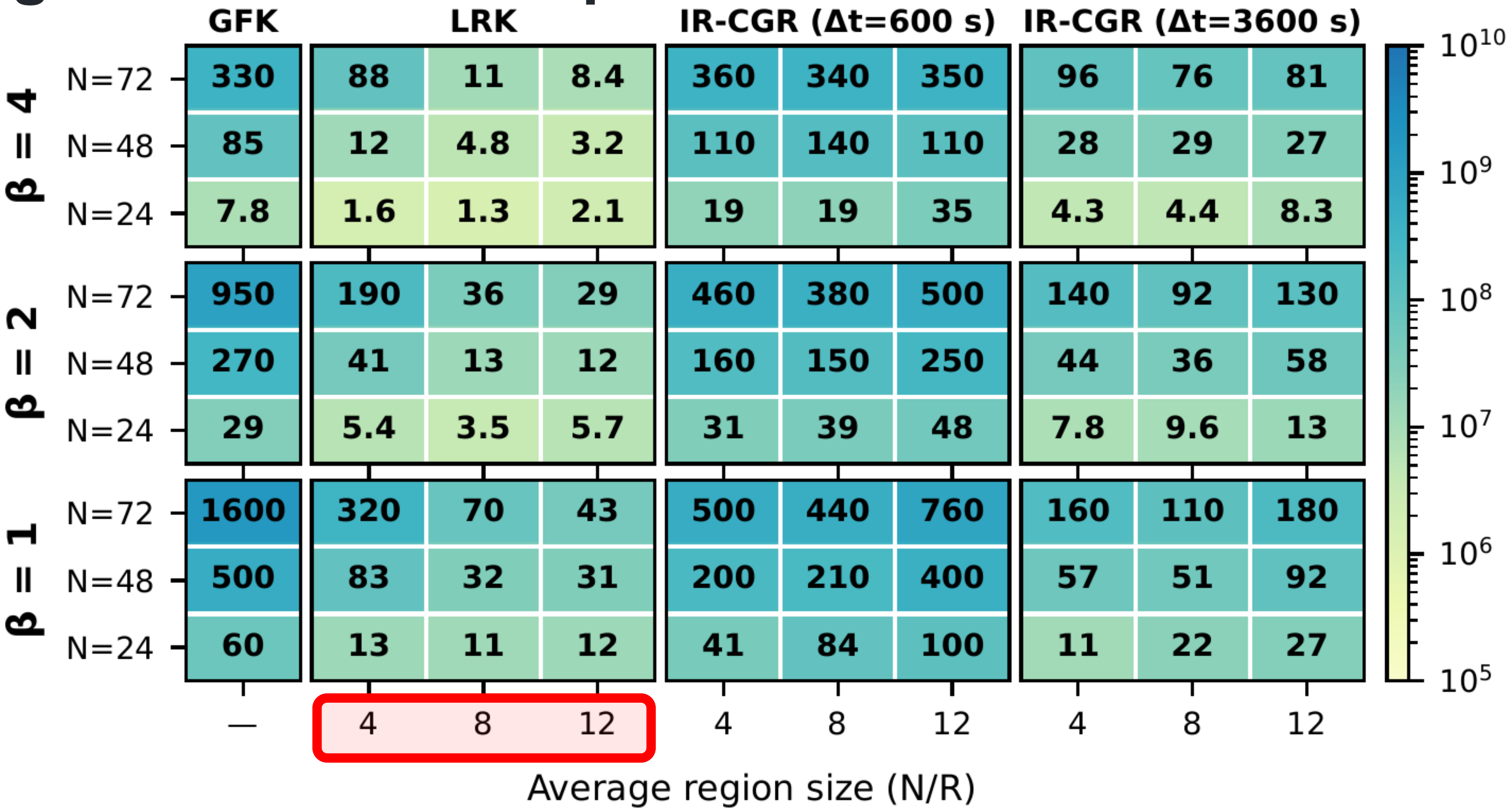

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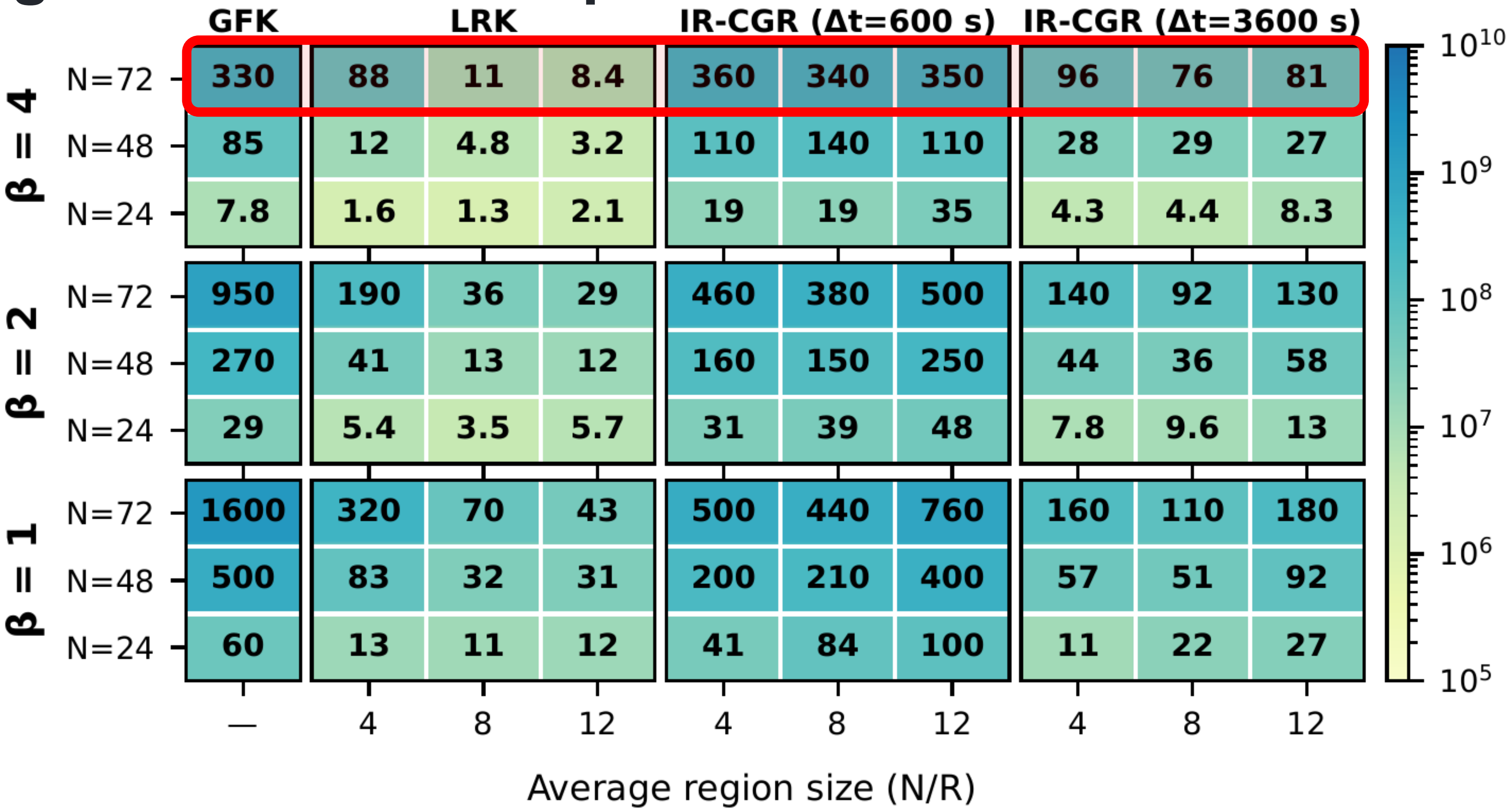
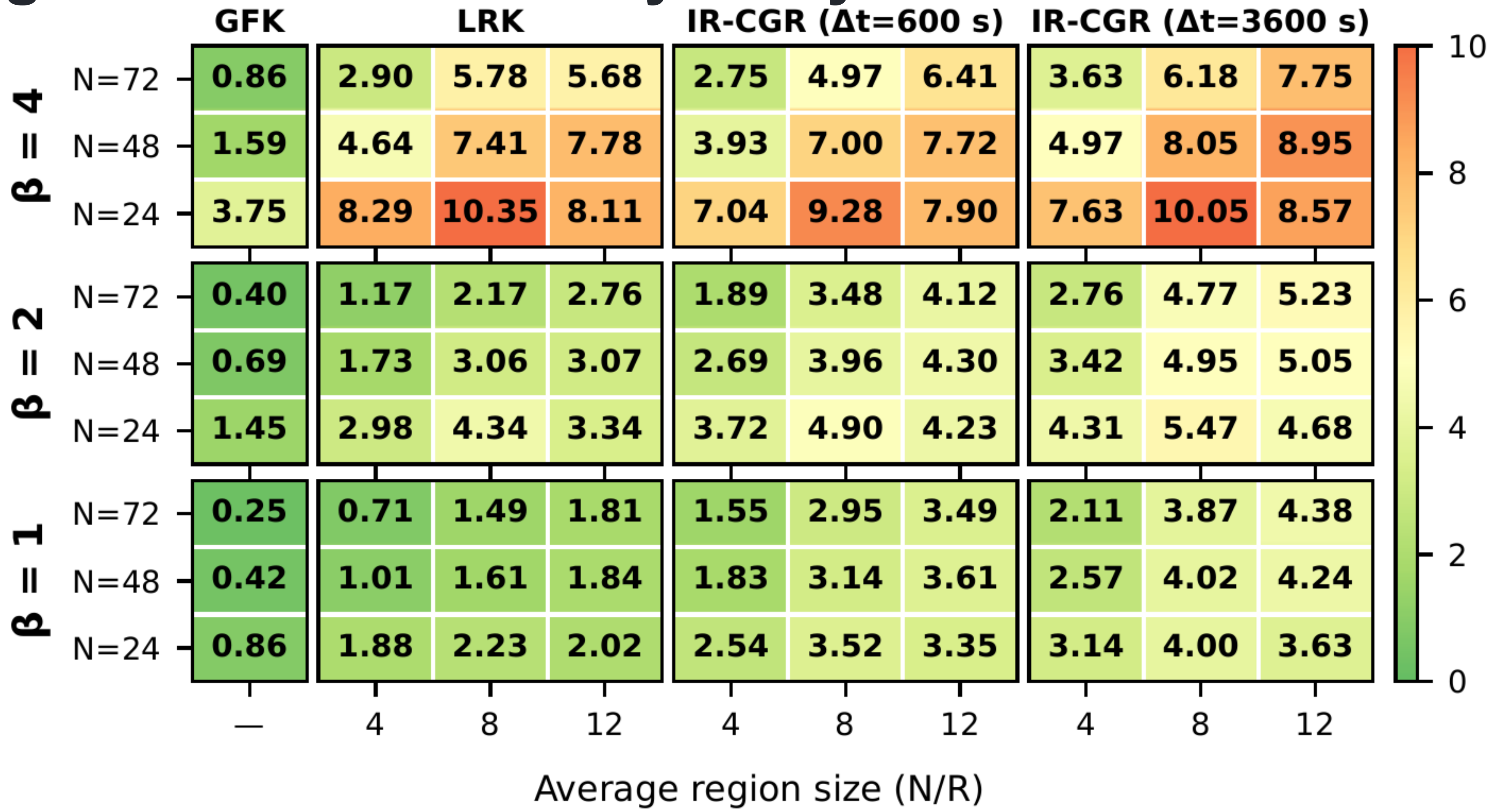


IR-CGR is usually more expensive than LRK,
but can remain much cheaper than full-plan GFK as the network grows.

Cell = 20-seed mean; DD [h]

Scaling Benchmark: Delivery Delay



Both regionalized methods show substantially higher delay than GFK.
In this benchmark, IR-CGR often does not improve delay over LRK.

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Summary

Problem

LRK reduces routing knowledge, but its static inter-region routing loses contact timing information.

Proposal

IR-CGR keeps contact windows between regions and applies CGR-style earliest-arrival routing on a compact IRCP.

Result

Overall, IR-CGR is most valuable under sparse, time-varying inter-region connectivity, while LRK remains attractive when inter-region connectivity is sufficiently rich and stable.

References

[1] J. A. Fraire, O. De Jonckère and S. C. Burleigh, “Routing in the Space Internet: A Contact Graph Routing Tutorial,” Journal of Network and Computer Applications, vol. 174, p. 102884, 2021.

[2] P. G. Madoery, J. A. Fraire, F. D. Raverta, J. M. Finochietto and S. C. Burleigh, “Managing Routing Scalability in Space DTNs,” in Proc. 6th IEEE Int. Conf. Wireless for Space and Extreme Environments (WiSEE), Huntsville, AL, USA, 2018, pp. 177–182.

[3] M. Feldmann, J. A. Fraire and F. Walter, “Tracking Lunar Ring Road Communication,” in Proc. IEEE Int. Conf. Communications (ICC), Kansas City, MO, USA, 2018, pp. 1–7