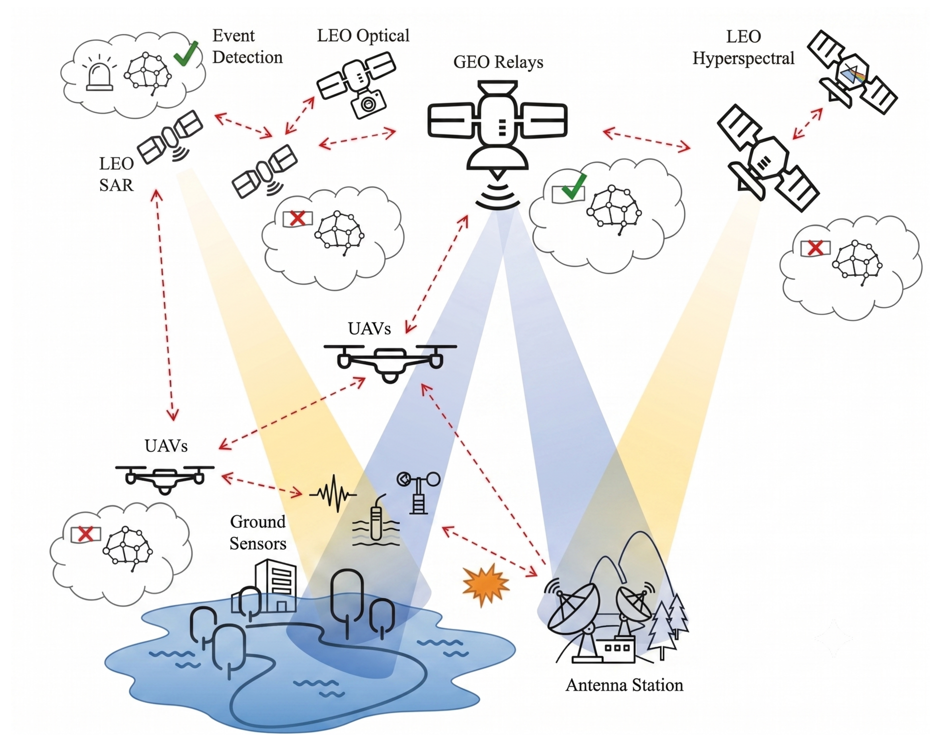
Critical Analysis of Heterogeneous Earth Observation Networks for Quantum-Enabled Climate Monitoring

Priyank Dubey Daniel Selva
Department of Aerospace Engineering, Texas A&M University

TEXAS A&M UNIVERSITY
Department of Aerospace Engineering

Motivation & Problem

- Fast-evolving climate and weather phenomena (flash floods, coastal surges, wildfires) change state in minutes to hours. Capturing their changing state requires joint, time-correlated observations from complementary sensors, rather than from a single platform.
- A heterogeneous web of space-air-ground sensors (LEO imagers/altimeters, UAVs, in-situ gauges, GEO relays, ground stations) must behave as one coherent instrument.
- Joint design and planning of such an architecture is combinatorially explosive and challenging for classical optimization methods.
- Before addressing this directly, we first ask a fundamental question: can the network coordinate inside each event's effective time window or decorrelation window (DECORR)?



Exemplary system: Nodes detect events of interest, issue task requests, and autonomously coordinate multi-sensor observations across the heterogeneous sensor web. (Credit: 3D-CHESS, TAMU & NASA)

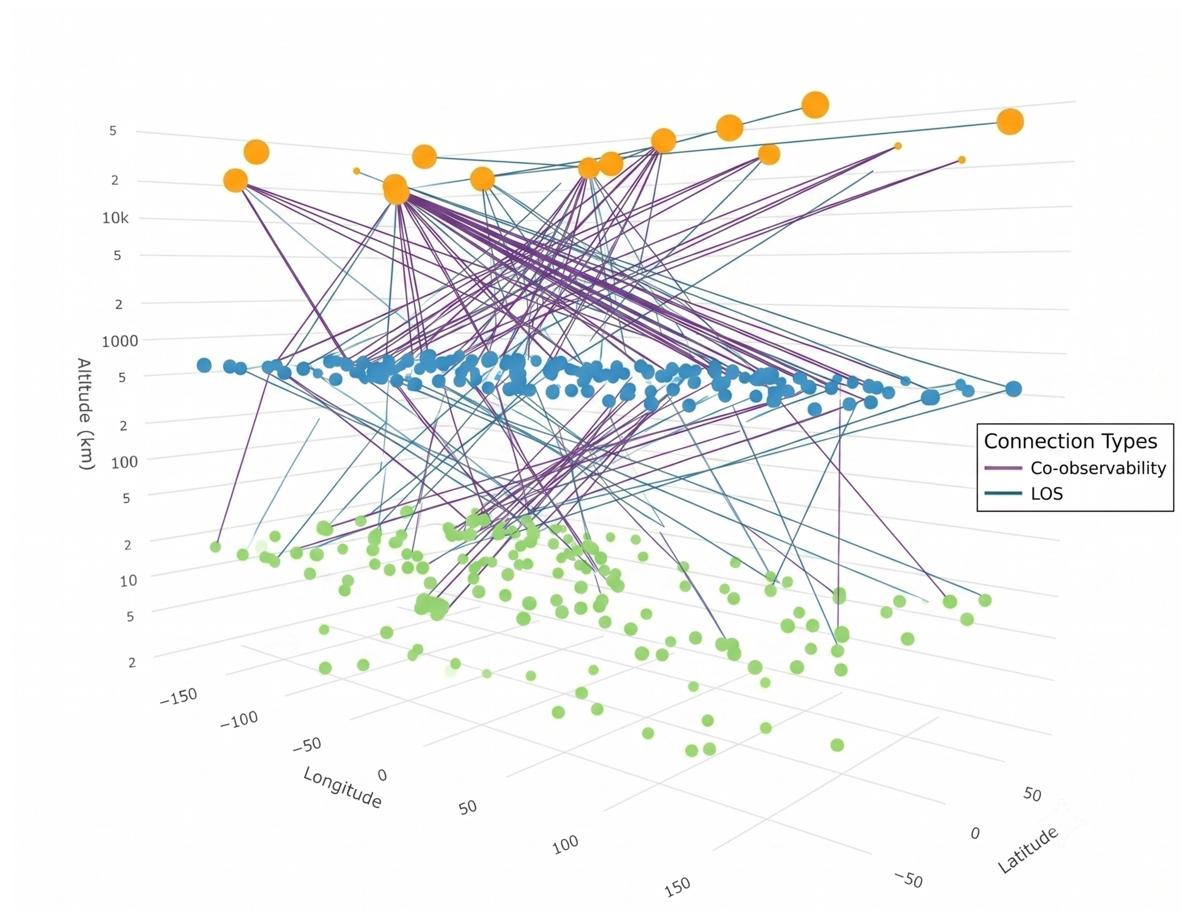


Fig. A. Interaction graph in latitude–longitude–altitude coordinates. Nodes represent assets; teal links indicate line-of-sight communication and purple links indicate scientific co-observability.

Why DECORR matters. After an event's decorrelation window, the physical state has changed enough that late co-observations are no longer jointly informative. It limits the responsiveness/coordination speed of the network.

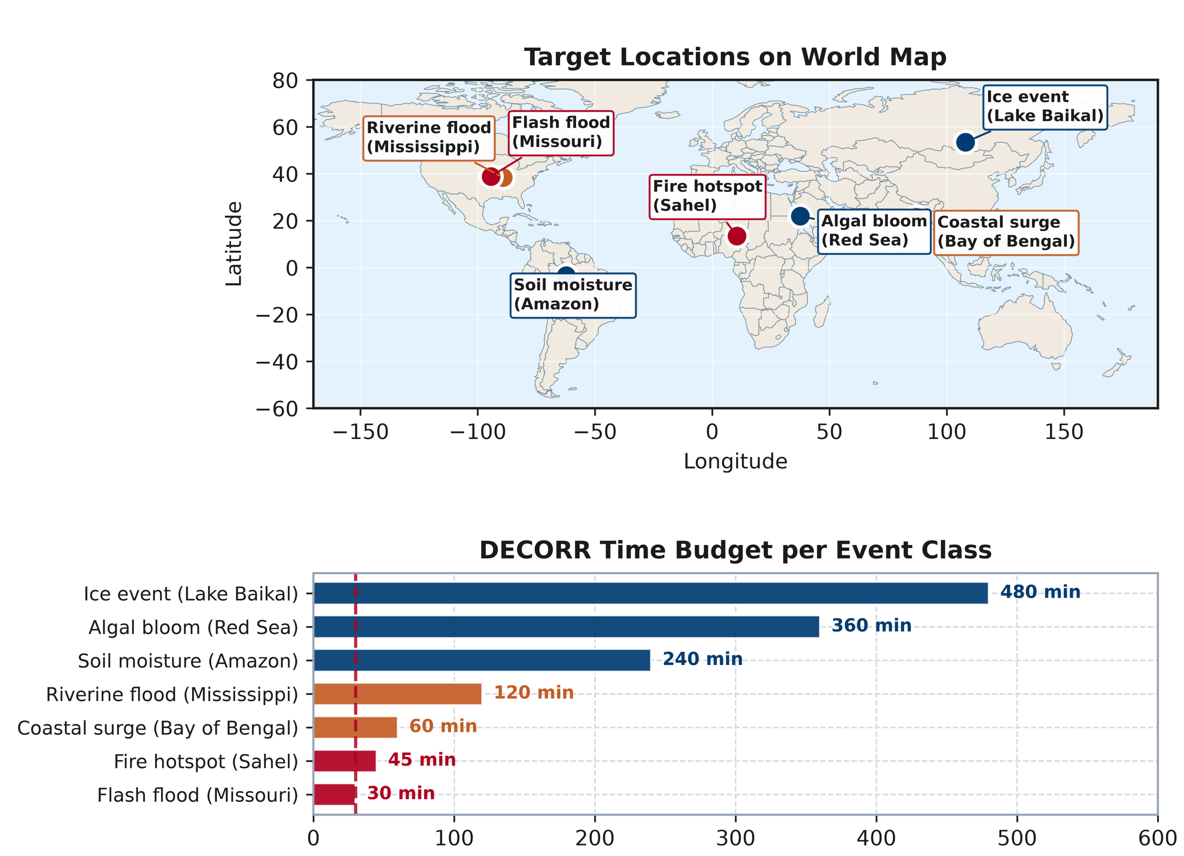


Fig. A2. Top: seven representative targets on the world map (Mississippi riverine flood, Missouri flash flood, Amazon soil moisture, Bay of Bengal surge, Sahel fire, Lake Baikal ice, Red Sea algal bloom). **Bottom:** Corresponding DECORR windows as the hard temporal budget for multi-sensor co-observation.

Research Questions

1. **Scale:** How do we keep joint scheduling tractable as the heterogeneous network grows?
2. **Feasibility (focus):** Given a heterogeneous sensor network, can it coordinate fast enough to capture the event state within its DECORR, and will that coordination remain robust under failures? Where are the bottlenecks?

Methodology

We model this as a joint **communication + science** complex network over heterogeneous assets, including GEO relays, LEO SAR, optical, and altimeter satellites, UAVs, ground instruments, and ground stations. The representative network contains $N{=}46$ assets and $M{=}918$ links sampled every $\Delta t{=}5$ minutes over a 24-hours simulation window. Edge weights combine LoS / range / bandwidth with co-observation synergy inside class-specific DECORR windows ($A = \frac{1}{2}w_C + \frac{1}{2}w_V$; Fig. **A**). The mission value is computed by summing co-observability edges contributions, based on whether their two assets can jointly observe an event within that event's DECORR.

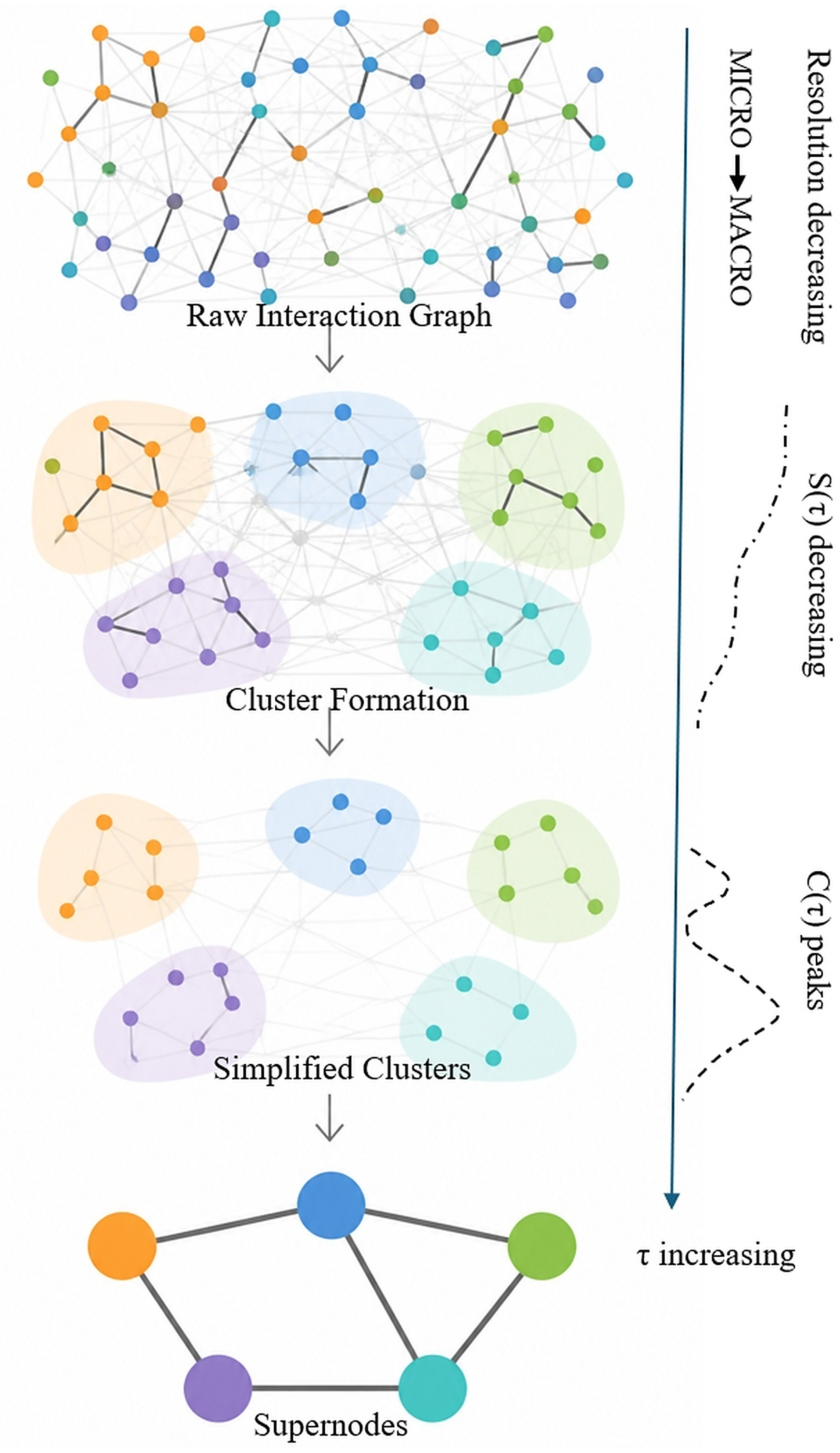


Fig. B. Our RG-inspired approach: As the diffusion timescale τ increases, assets merge into supernodes purely by interaction strength. Entropy $S(\tau)$ falls while specific heat $C(\tau)$ peaks at intrinsic time-scales, marking critical coordination transitions.

- **Multiscale RG Analysis:** We group strongly and fast-interacting assets into supernodes across increasing scales, tracking entropy $S(\tau)$ and specific heat $C(\tau)$ to detect where the network naturally reorganizes. Peaks in $C(\tau)$ locate the intrinsic coordination timescales τ^*.
- **Role Classification:** At each τ^*, a diffusion density-matrix analysis $\rho(\tau^*)$ of each asset's coupling to the rest of the network labels it as a Core-Hub (broad influence), Supernode-Bridge (connects separate clusters), Anchor (stable within one cluster), or Bottleneck (weakly connected but structurally necessary), directly from topology, with no dynamical simulation required.
- **Percolation & Stress Tests:** We remove links both randomly and by importance, tracking two thresholds: f_{V50}, the fraction removed before aggregate mission value drops to half, and f_c, the fraction removed before the Fiedler eigenvalue hits zero and the network fragments. Hence, f_{V50} tracks, the gradual loss of scientific observation, and the f_c captures complete failure where the network structurally disconnects.
- **MILP Validation:** We independently confirm these topology-based feasibility predictions using a classical mixed-integer linear programming (MILP) schedule on the network under degradations.

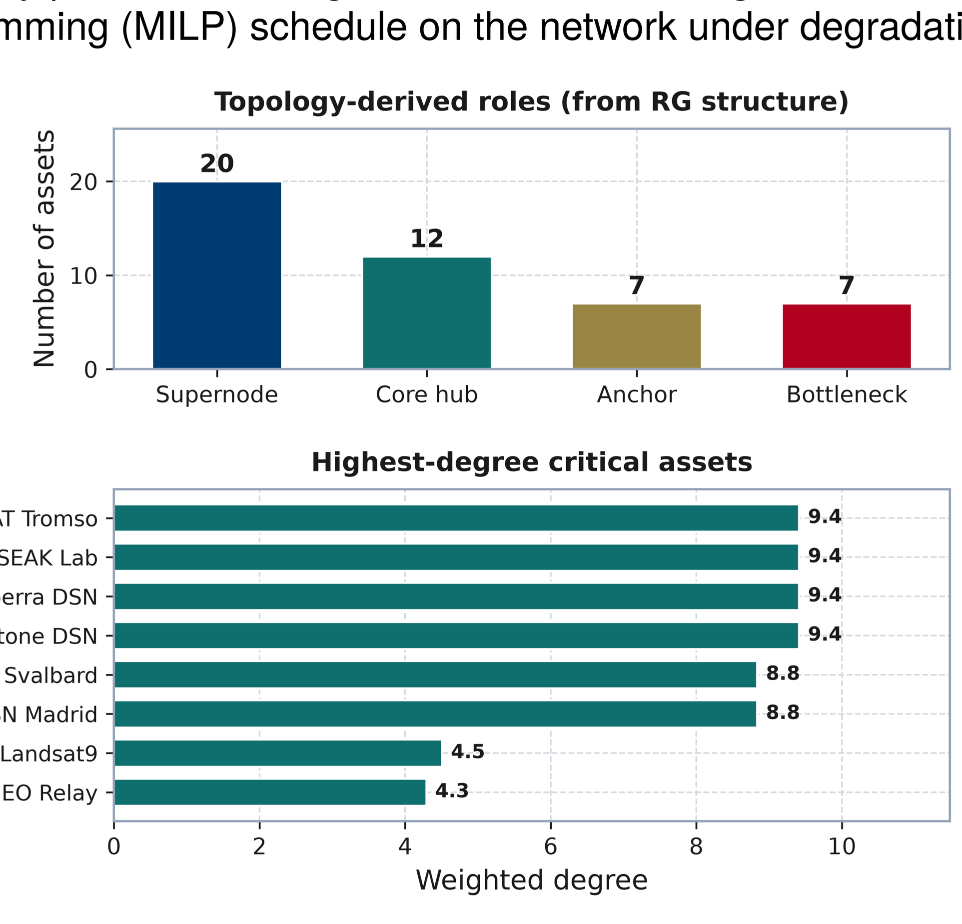


Fig. C. (**Top:**)Topology-derived asset roles assigned via spectral graph structure (density-matrix row sums, degree, and betweenness centrality).(**Bottom:**) Highest-degree critical assets targeted for stress-testing.

$$\rho(\tau) = \frac{e^{-\tau L}}{\mathrm{Tr}(e^{-\tau L})} \qquad S(\tau) = -\mathrm{Tr}(\rho \log_2 \rho) \qquad C(\tau) = -\frac{dS}{d\ln\tau}$$

Results & Discussion

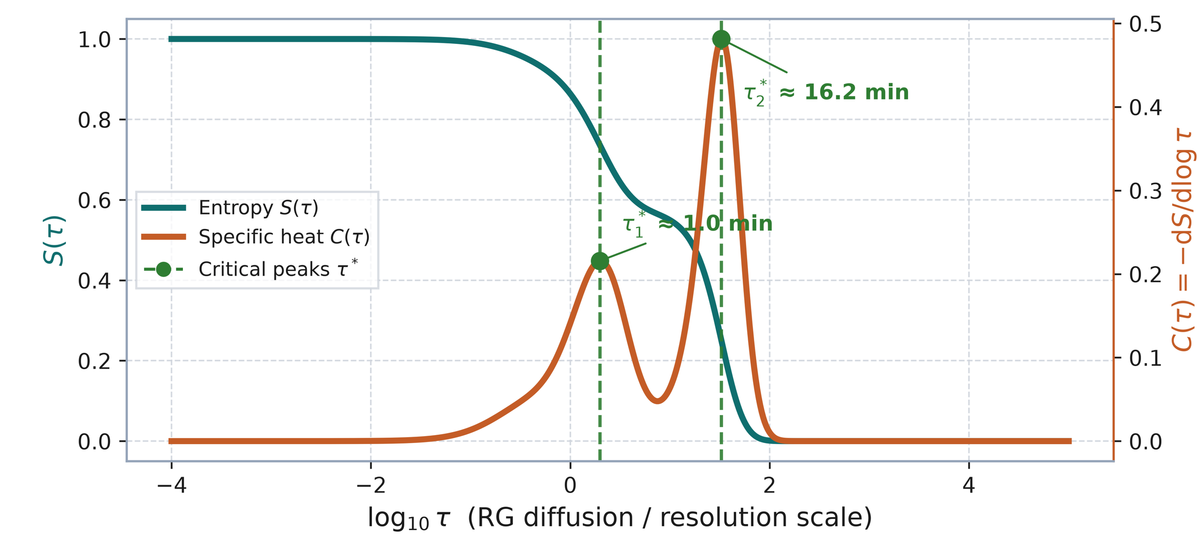


Fig. R1. Coordination timescales: peaks of $C(\tau)$ yield $\tau_1^* \approx 1.0$ min (fast, same-type coordination) and $\tau_2^* \approx 16.2$ min (slow, cross-type relay).

- Both timescales emerge directly from diffusion reorganizations in $C(\tau)$, with no dynamical simulation required.
- The entropy drop from $S(\tau_1^*){=}0.74$ to $S(\tau_2^*){=}0.25$ confirms a clear fast-to-slow coordination hierarchy.

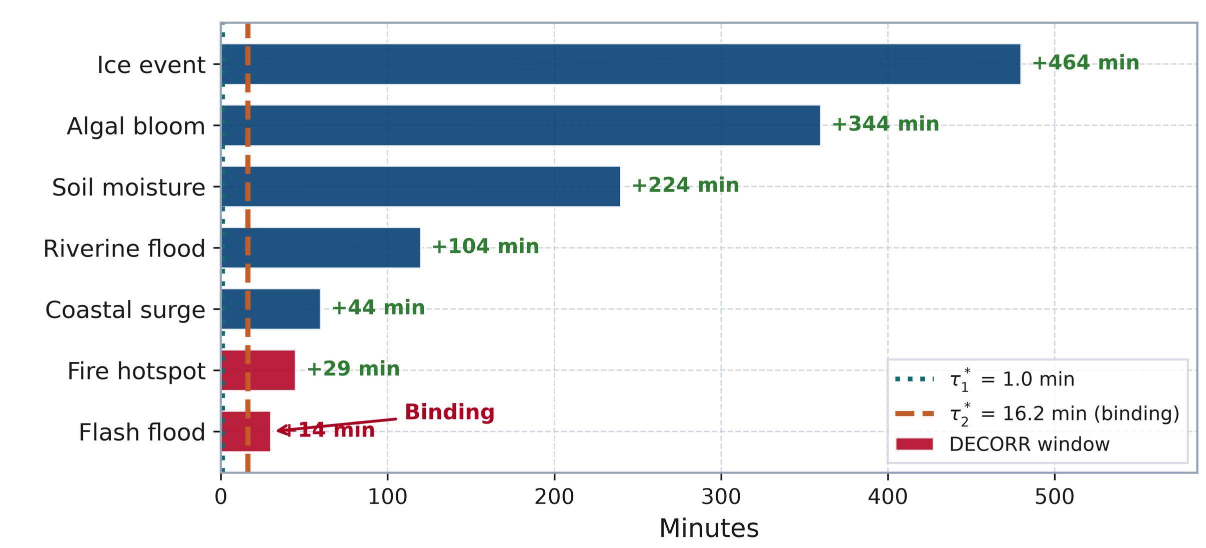


Fig. R2. Baseline feasibility: $\tau_2^* = 16.2$ min lies below all DECORR windows (7/7 feasible validated by MILP).

- Flash flood is the tightest case (DECORR $= 30$ min), giving only a $1.85\times$ margin ($30/16.2$) and flagging the first structural vulnerability.
- These are hard physics bounds from graph topology alone, established before any optimization solver runs.

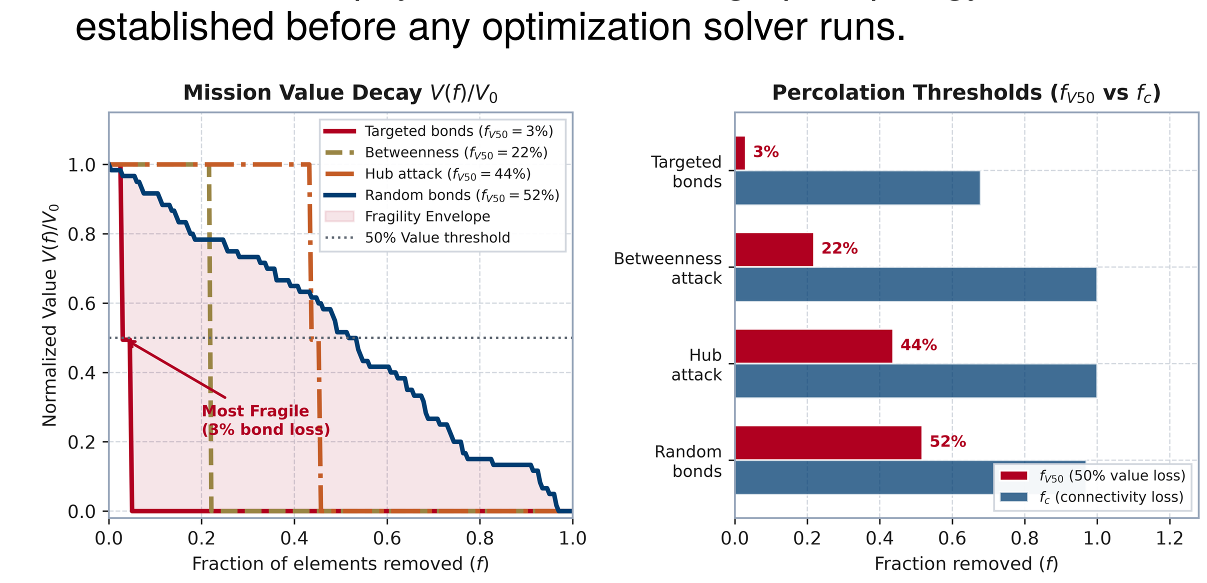


Fig. R3. Mission value decay $V(f)/V_0$ with shaded fragility envelope (left); percolation thresholds comparing mission value half-life (f_{V50}) vs. connectivity collapse (f_c) across four attack modes (right), showing a $17\times$ fragility gap ($f_{V50} \approx 3\%$ targeted vs. 52% random).

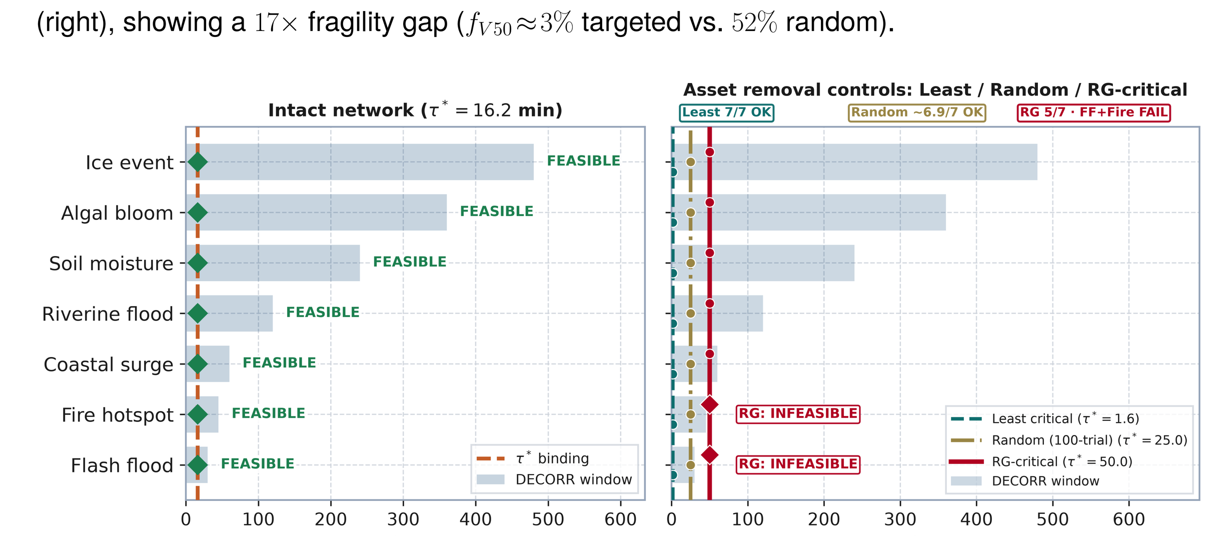


Fig. R4. MILP-validated closed-loop control experiments under 9/46 assets removal.

- Re-evaluating degraded networks flips Flash flood margin (+13.6 → −20.0 min) and Fire margin (+28.6 → −5.0 min) to [INFEASIBLE], and MILP control experiments (intact N=46 vs. four 9-asset removals at N=37) match our RG predictions: least-critical and random removals keep ≈7/7 missions feasible, and RG-critical removal drops to 5/7. (Margin = DECORR - τ^*)

Key Takeaways

- **Resilience is highly asymmetric:** Across 5 removal policies, least-critical ($\tau^*{=}1.6$ min) and random ($\tau^*{=}24.0$ min) removals leave all missions feasible (7/7), while RG-critical removal breaks 2/7 ($\tau^*{=}50$ min) and highest-degree removal collapses 5/7 ($\tau^*{=}298.6$ min).
- **Criticality, not asset count, drives failure:** The same 9-asset budget is harmless on peripheral nodes but selectively infeasible on RG-identified bridges, isolating structural role, not removal size, as the causal factor.
- **Network dynamics and MILP agree event-by-event:** A Gurobi MILP scheduler independently reproduces the same feasibility outcome as our network dynamics analysis in all 5 scenarios.

References

1. P. Villegas et al., *Laplacian renormalization group for heterogeneous networks*, Nature Physics **19**, 445–450 (2023).
2. B. Gorr, D. Selva. *Decentralized Satellite Constellation Replanning for Event Observation.* **JSR, 2025.**