Graph-theoretic Performance Analysis for Constellation Link Geometry via Random Geometric Networks

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The Big Questions

- How Does ISL range affect satellite network robustness?
- Can simpler network models like random geometric graphs predict the behavior of complex satellite constellations?

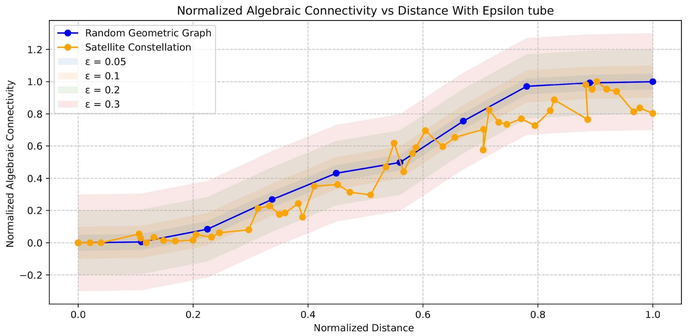
Our Approach

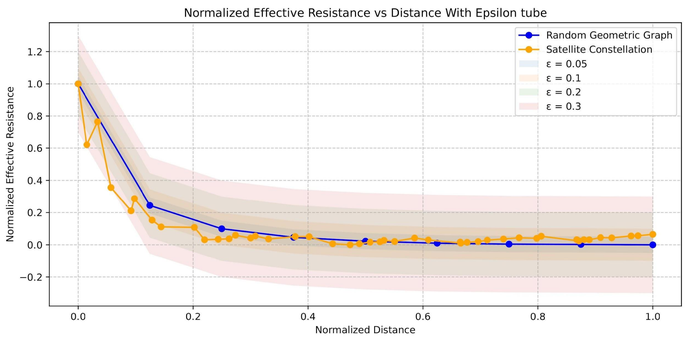
- **Satellite Constellation Model:**
- Based on SpaceX parameters (550 km altitude, 32 planes, 50 satellites per plane
- Constrains: Max degree 4, field of view, reciprocal connections
- Greedy algorithm for link selection
- **Random Geometric Graph(RGG) Model:**
- Nodes uniformly distributed on a spherical shell
- Max degree 4 is the only constraint
- Same link selection algorithm as satellite constellation
- **Key Robustness Metrics Analyzed**
- Algebraic Connectivity $\lambda_2(\mathrm{L}(\mathrm{G}))$: Overall network connectivity
- Effectivity Resistance $R_{eff}(G)$: Communication efficiency, account for all paths
- Latency (Average Shortest path length l_G)
- $$t_l = \frac{d_{ij}}{c} + l_G t_p$$
- **Dynamic Weighted Graph Method:**
- Removes all the constrain and link selection algorithm
- $$W_{ij} = 1 - \frac{1}{1+e^{k(d_{ij}-m)}}$$

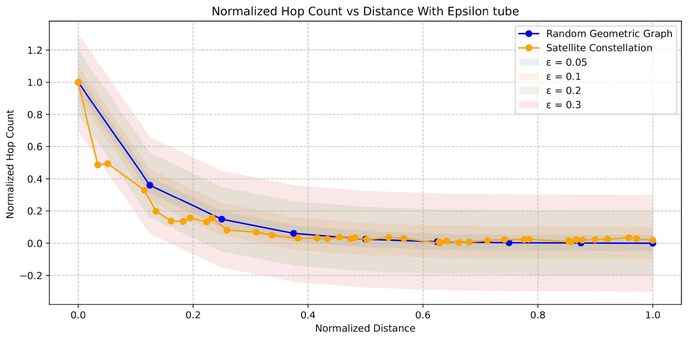
Key Findings

- **ISL Range & Robustness:**
- Increased ISL range improve all robustness metrics
- Saturation points: Beyond a threshold, improvements diminish significantly (sigmoidal trend)
- **Satellite Constellation vs. RGGs:**
- Remarkable similarity, RGGs show very similar trends in $\lambda_2(\mathrm{L}(\mathrm{G}))$, $R_{eff}(G)$ and t_l
- **Weighted Graph Analysis:**
- Re-confirm similarity in algebraic connectivity between these two networks.
- Both show similar mean and distributional shift with varying weight

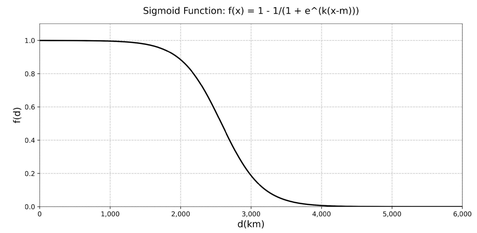
Results

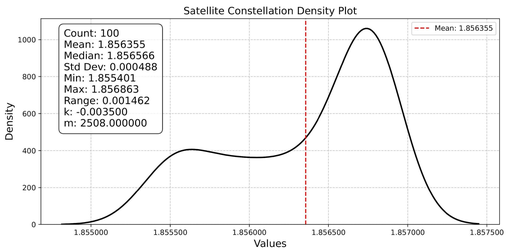


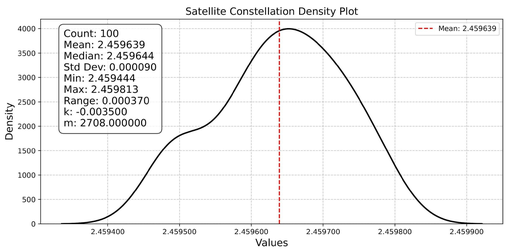


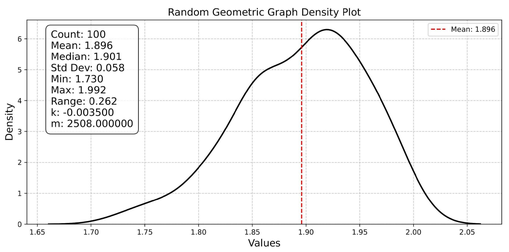


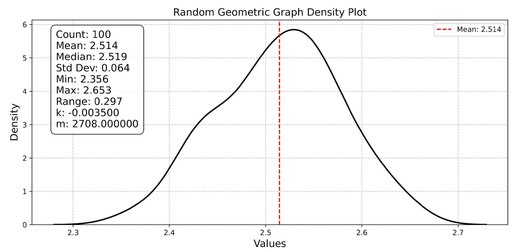
Weighted Graph Analysis











Conclusion & Future Works

- ISL range is a critical design parameter with a clear saturation point for robustness gain
- RGGs demonstrate similarities to complex stellation constellation
- This suggest RGGs can serve as computationally efficient proxies in early-stage satellite constellation design
- Develop analytical results to formally explain the observed similarity
- Investigate the impact of orbital perturbations and other real world complexity

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