Preliminary Evaluation of HPC-Based Scenario Analysis for Dense Formation Flying

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1 Introduction

Small satellites have lowered the barrier to space missions, enabling flexible, low-cost constellations such as Starlink that provide global broadband. Building on this trend, Direct-to-Device (D2D) services aim to let smartphones and IoT devices communicate directly with satellites without additional hardware. However, broadband D2D links at terrestrial-like rates demand very large effective apertures on the satellite side, typically using large antennas or phased arrays, whose size, mass, and deployment are severely constrained. We previously proposed using dense formation flying (FF) of multiple PicoSats as a distributed phased array antenna (PAA) for broadband D2D services [1]. In this concept, many nearby PicoSats fly in coordinated orbits with tightly controlled relative positions and attitudes, and together act as a single large distributed PAA (Fig.1). This architecture can leverage mass production, built-in redundancy, and flexible in-orbit reconfiguration of the array geometry.

Realizing such a system poses substantial control and analysis challenges. Each satellite is perturbed by effects such as Earth's oblateness (J2), atmospheric drag, and solar radiation pressure, and the design space spans formation geometry, orbital altitude, inter-satellite spacing, disturbance models, and control strategies. Exploring this space requires simulating a very large number of scenarios, each involving high-precision orbit propagation for 10,000 satellites.

This paper focuses on HPC-based scenario analysis for systems targeting broadband D2D communications. To explore this high-dimensional design space, we employ large-scale scenario-level parallelism to conduct parameter sensitivity analysis and prune low-impact factors from the design space. This serves as a basis for reducing the design space prior to more computationally intensive optimization. Extending this framework to evolutionary computation and broader scenario evaluations, including failure and anomaly cases, is left as future work.

2 Challenges and Approaches

Computational Cost: We have developed a large-scale FF simulator that integrates high-fidelity orbit propagation models from the Orekit library, including major perturbations such as the Earth's J2 term and atmospheric drag. These models require repeated numerical evaluations during propagation, substantially increasing the per-satellite computational cost. As a result, propagating 10,000 satellites over a single LEO orbit requires several tens of minutes of wall-clock time on a single node, indicating the limited scalability of single-scenario execution.

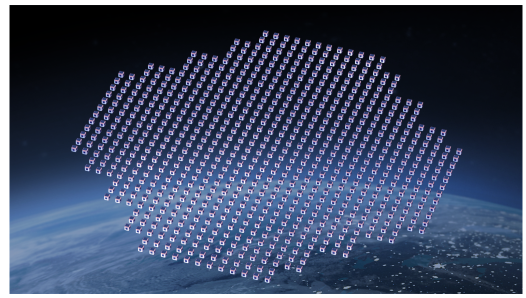

Figure 1: A concept illustration of Formation-Flying Phased Array Antennas (FFPAA) [1]

Number of Scenarios: Our simulator implements a wide range of configurable parameters relevant to dense formation flying. Exploring different combinations of these parameters results in a large number of scenarios. Running high-cost orbit-propagation simulations across a large number of scenarios would be impractical without acceleration through large-scale scenario-level parallelization on HPC systems.

To address these challenges, we exploit two layers of parallelism on the supercomputer. At the scenario level, more than 100 scenarios are executed concurrently across multiple nodes. At the intra-scenario level, each scenario uses MPI across a full node (48 cores) to parallelize orbit propagation for thousands of satellites.

On this parallel execution framework, we currently perform parallel sensitivity analysis to identify parameters that strongly affect relative position error. As an evaluation indicator, we consider formations of cube-shaped satellites with a side length of 50mm, arranged with 80mm spacing, and analyze their relative position error.

As future work, we plan to incorporate evolutionary computation to search for configurations that minimize these errors, and to extend our study to more comprehensive scenario evaluations, including satellite failures and other anomaly cases, using the same large-scale parallel infrastructure.

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References

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