Hybrid Quantum–Classical Optimization for

Satellite Constellation Design and Orbital Debris Management

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***Abstract*—The rapid expansion of satellite constellations and the growing density of orbital debris have intensified the need for advanced computational tools capable of optimizing orbital architectures, collision avoidance, and long-term space sustainability. Traditional optimization methods are increasingly constrained by the combinatorial complexity of constellation design variables—including orbital planes, phasing, revisit requirements, and communication coverage—and the nonlinear dynamics of debris propagation. This study introduces a hybrid quantum–classical optimization framework that integrates quantum approximate optimization algorithms (QAOA), quantum annealing, and classical multi-physics orbital simulation to improve decision-making in constellation deployment and debris mitigation. Quantum subroutines accelerate the search for globally efficient orbital configurations, while classical solvers handle high-fidelity astrodynamics, propagation models, and mission constraints. Preliminary simulation results indicate that the hybrid framework yields more efficient constellation geometries, reduces collision risk, and enhances debris avoidance planning compared to classical baselines. These findings highlight the potential of quantum-assisted optimization to support safer, more resilient, and sustainably managed space systems.**

The proliferation of satellite constellations in low Earth orbit (LEO) has enabled unprecedented capabilities in global communication, Earth observation, and navigation services [3]. However, this surge in satellite deployments has also intensified pressures on orbital environments, contributing to congestion and increasing the probability of collision cascades—a phenomenon highlighted by the growing body of research on orbital debris dynamics [4]. As space systems evolve toward mega-constellations, optimizing their design and ensuring long-term space sustainability have become critical scientific and technological challenges. Solutions require balancing multiple factors: coverage performance, launch costs, orbital slot allocation, collision avoidance maneuvers, and the evolving debris environment driven by atmospheric drag, fragmentation events, and mission lifetimes [5].

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Classical optimization strategies—including heuristic search, evolutionary algorithms, and multi-objective optimization—have supported constellation design for decades [2]. Yet, these methods confront significant computational burdens when navigating the exponential design space formed by orbital parameters, phasing arrangements, inter-satellite links, and coordination with existing orbital assets. Moreover, integrating real-time debris tracking, risk forecasting, and dynamic collision avoidance demands algorithms capable of processing highly non-linear, stochastic, and multi-constraint models [6].