IAF SPACE COMMUNICATIONS AND NAVIGATION SYMPOSIUM (B2)
Advances in Space-based Communication Systems and Services, Part 1 (2)

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TOWARD AUTONOMOUS COOPERATION IN HETEROGENEOUS NANOSATELLITE CONSTELLATIONS USING DYNAMIC GRAPH NEURAL NETWORKS

Abstract

The unprecedented potential of Distributed Satellite Systems (DSS) to improve mission performance by coordinating efforts between different satellites calls for new autonomous mission planning and scheduling methods that adapt to dynamic environments. The upcoming landscape of Earth Observation (EO) missions will be defined by network-enabled heterogeneous nanosatellite constellations designed to fulfill stringent mission requirements in terms of revisit times, coverage areas, spatial resolution, and data latency. Given that autonomous cooperation between satellites managed by different operators can increase the scientific return by sharing unused resources and downlink opportunities, innovative networking and coordination techniques for nanosatellite systems are needed.

One of the key problems in this context is how to compute communication opportunities and efficiently generate a global satellite contact plan. Numerous solutions propose using ground facilities to propagate orbit trajectories and compute the corresponding plan, requiring extensive coordination efforts from the different operators. Moreover, the launch of new satellites or the removal of existing ones entails updating the contact plans and introduces further dependency from the ground segment. Solutions involving onboard orbital propagation do not scale well due to the limited computational resources onboard nanosatellites. We argue that the benefits of autonomous cooperation under the restrictions introduced by the scale and heterogeneity of the future EO constellations have not been sufficiently studied.

To address this gap, we propose modeling heterogeneous satellite constellations as dynamic networks and applying graph-based methods to generate a satellite contact plan. We implement a state-of-the-art dynamic graph neural network (DGNN) that combines the capabilities of graph neural networks (GNN) to capture spatial information and recurrent neural networks (RNN) to capture the temporal components. We consider this solution a first step towards a distributed algorithm for autonomous cooperation between satellites. The main advantage of this learning-based approach is maintaining a system-level perspective of the constellation while adapting to changes such as the addition and removal of satellites.

To assess the performance of our algorithm in different constellation sizes and degrees of connectivity, we simulate operational use cases of low earth orbit (LEO) constellations with increasing dimensionality, communication opportunities, and network changes. The results identify scenarios where our method efficiently generates a satellite contact plan. We find that the studied cases present several tradeoffs in prediction accuracy and missed cooperation opportunities and analyze them in-depth. Finally, given the capabilities of our method, we discuss how additional network and topology information could be extracted using our formulation.