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A MULTI-LAYER TEMPORAL NETWORK MODEL OF THE SPACE ENVIRONMENT

Abstract

With the advent of the New Space era and the increase in the population of resident objects in Earth orbit, there is a compelling need to adopt new tools to study the complexity of the space environment. In particular, there is a need to consider the different layers of functionalities and services in an integrated and consistent framework that allows a global analysis of the evolution of the space environment. In the past two decades, there has been intense research to describe and model physical, engineering, information, social and biological systems using network theory. Most recently, multi-layer networks, or networks of networks, have demonstrated a higher capability of describing failures, relationships, connectivity, and patterns, with respect to their single-layer counterpart.

This paper presents a novel multi-layer temporal representation of the space environment, where space objects are nodes and their relationships are captured through dynamic links. Each layer represents a different type of interaction. In this paper, in particular, we consider two layers: the physical and the information layer. The former layer models the probability of a collision between pairs of objects and the insurgence of anomalies due to collisions or space weather effects, while the latter models the exchange of information via telecommunication. Links are time-dependent and probabilistic in that they model the probability of an interaction between two nodes.

With this model, we investigate a percolation problem in a simple system composed of a mix of active and inactive objects by removing and adding both nodes (site percolation) and links (bond percolation). In this way, we are capable of understanding how a maneuver (i.e., a variation in the link probability) or the addition of new satellites (i.e., the appearance of more nodes at certain layers) affects the overall robustness and global performance of the system. We also show how changes in the network topology can be used to identify weak links and nodes, sub-networks and study their time evolution.

Furthermore, we analyze the eigenspectrum of the supra-Laplacian tensor associated with the multi-layer network and, from that, we study the coupling between intra and inter-layers relationships and their dynamical features (e.g., what are the links that are more critical in terms of speed of change and strength values).