Distributed topology control in networked multi-agent systems based on consensus protocol and graph neural networks

Marko Križmančić
Faculty of Electrical Engineering and Computing
University of Zagreb
Zagreb, Croatia
marko.krizmancic@fer.hr

Stjepan Bogdan *(supervisor)*
Faculty of Electrical Engineering and Computing
University of Zagreb
Zagreb, Croatia
stjepan.bogdan@fer.hr

***Abstract*—This research aims to develop a distributed, adaptive, and scalable method for controlling communication topology in networked multi-agent systems. The method uses algebraic connectivity tracking and resilience optimization, using a consensus protocol for estimating the global topology through local communication. Agents converge to a common state and collectively select the best link(s) to add or remove using a heuristic or novel graph neural network (GNN) method. Additionally, a new GNN model will enhance system resilience without compromising desired connectivity.**

***Index Terms*—multi-agent system, topology, consensus, GNN**

I. INTRODUCTION

Distributed networked systems are becoming an increasingly popular solution to address various challenges of modern life. In such systems, each entity represents an autonomous intelligent agent that contributes its part to the collective objective, hence, they are often referred to as multi-agent systems (MAS). These systems find applications in a wide range of domains, such as robotics, transportation, computer and social networks, and energy grids [1].

One of the key challenges associated with MAS is to enable agents to realize a common goal despite their diverse capabilities and limited knowledge of the environment. Since real-world communication can degrade rapidly due to interference, obstacles, and agent failures, limited information exchange among agents can negatively affect system performance [2]. However, expansive communication requires increasing the number of links, which can lead to delays due to token exchange, and increased energy consumption.

The communication network of a MAS can be modeled as an undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, with vertices $\mathcal{V}$ representing agents and weighted edges $\mathcal{E}$ describing the state of the communication channel between them. In this case, the overall level of connectivity of the system can be determined by algebraic connectivity - the second smallest eigenvalue of the graph's underlying Laplacian matrix, $\lambda_2(\mathbf{L}(\mathcal{G}))$. Algebraic connectivity is often used in research on networked systems because it is a fundamental measure of system performance [3].

Most of the work on topology control is only concerned with maximizing connectivity, either absolutely or within a given budget [4]. However, keeping the algebraic connectivity at a maximum level does not necessarily contribute to the quality of control due to delays, redundancy of messages, and increased energy consumption. Thus, the goal of connectivity control, and our work, is to regulate the communication graph so that λ_2 tracks the given reference value through time.

II. METHODOLOGY

In a fully decentralized system, this task is non-trivial since each agent has only local knowledge about its neighborhood. Therefore, information about the other communication links must be propagated through the network. To estimate the overall system topology in a distributed way, we propose the following update rule for the consensus protocol:

$$a_{ij}^l(k+1) = a_{ij}^l(k) + \sigma \Delta a_{ij}^l(k) \tag{1}$$

$$\Delta a_{ij}^l(k) = \sum_{p \in \mathcal{N}_l} a_{lp}^l(k) \left(a_{ij}^p(k) - a_{ij}^l(k) \right) + + \left(\tau_{ij}^l(k) - a_{ij}^l(k) \right),\ i \neq j, \tag{2}$$

where a_{ij}^l is the element of the adjacency matrix of agent l, describing its view on the link quality between agents i and j, $\mathcal{N}_l$ is a set of its neighbors, τ_{ij}^l is the measured value of the link quality, and σ is the update step size. By iteratively running the proposed update law on all agents, we ensure that they converge to a common value (the proof is given in [5])

$$\mathbf{A}^l(k) = \mathbf{A}\ \forall l, k \to \infty. \tag{3}$$

Once $\mathbf{A}$ is determined, each agent computes λ_2 and, depending on the deviation from the reference value modifies the graph by adding or removing links. This will in turn increase

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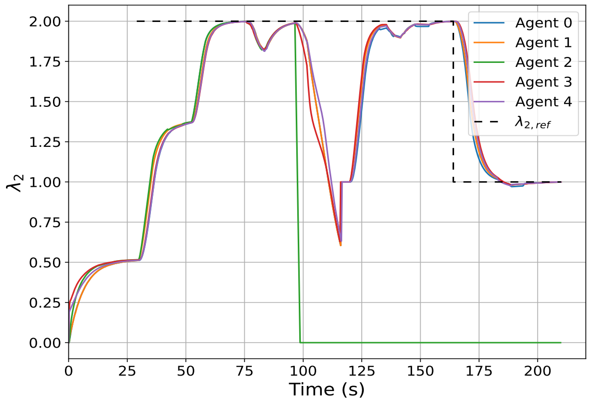

Fig. 1. Time response of algebraic connectivity estimates with a simulated failure of agent 2 at $t = 95$ s.

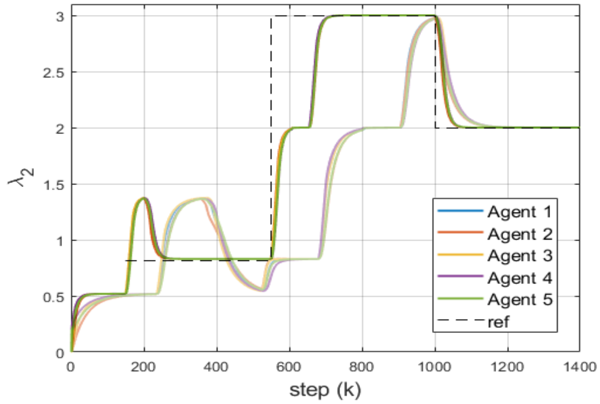

Fig. 2. Adaptation of parameter σ improves the performance of the networked system. Lighter colors represent the system without adaptation.

or decrease the value of λ_2 accordingly. The candidate link between agents i and j is evaluated using Fiedler's heuristic rule [4]

$$\frac{\partial \lambda_2}{\partial l_{ij}} \approx \mathbf{f}^T \frac{\partial \mathbf{L}}{\partial l_{ij}} \mathbf{f} = (f_i - f_j)^2, \tag{4}$$

where $\mathbf{f}$ is the eigenvector of the graph's Laplacian matrix, and f_i is its i-th element.

III. RESULTS

To show the effectiveness of the proposed topology control method, we conducted experiments in MATLAB simulation and with a distributed system consisting of Raspberry Pi 4 computers [6]. We initialize the agents only with information about their immediate neighbors so the overall estimated connectivity is equal to 0.

Fig. 1 demonstrates the ability of our algorithm to correctly estimate the initial connectivity of the network during $t \in \langle 0, 30]$ s and follow the desired reference in the remainder of the experiment. At $t = 95$ s, we simulate a failure of agent 2 by forcibly shutting it down. As other agents stop receiving messages from their neighbor, λ_2 of the graph drops rapidly. After about 10 seconds, the estimated adjacency matrices show that agent 2 is no longer responsive. The group makes a collective decision to exclude it from future computations and quickly reorganizes to restore the connectivity.

Fig. 2 shows preliminary results of using a novel adaptation mechanism for the parameter σ. Along with λ_2, it controls the convergence rate of the consensus, but can also cause instabilities. As shown, adapting its value according to the topology changes can improve the system performance significantly compared to using a fixed value.

IV. FUTURE WORK

Modifying links to achieve desired network connectivity is a challenging NP-hard problem, and existing heuristics often fall short when significant changes in connectivity are required.

Graph Neural Networks (GNNs) have recently become popular for their efficient handling of graph data and their ability to perform tasks such as node classification, link prediction, and clustering. These tasks are particularly relevant in the context of topology control. In our future work, we aim to leverage GNNs to predict and optimize the overall connectivity of a given graph by identifying critical nodes and edges. Additionally, we will explore utilizing GNNs to optimize network resilience while maintaining the desired connectivity levels. The final aspect of our future research involves the distributed deployment of the neural network on multiple devices. This approach is attractive because the nodes in the communication graph function similarly to neurons in the GNN model, updating their representations by exchanging messages over existing connections.

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