

Motif-based Topology Design for Efficient Performance by Networks of Mobile Autonomous Vehicles

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Networked systems of autonomous agents have emerged in a variety of applications such as collaborative robotics, mobile sensor networks and disaster relief operations. Complex phenomena are often observed in these systems due to the large number of agents, nonlinear interactions, locality of information transmission, and changes in the connectivity of the agents. Similar to their natural counterparts, engineered autonomous agents are capable of developing emergent behaviors such as herding, collaborative decision making based on local communication. The speed of developing emergent behaviors and their robustness to agents' failures depend on the underlying network connectivity and feasible communications. We study the interdependence of structure and behavior in a networked system of autonomous vehicles.

We have abstracted the collaboration between the vehicles into three interconnected levels. At each point of time, three graphs describe the network of moving vehicles: a *connectivity graph*, a *communication graph*, and an *action graph*. The first two graphs describe the information exchange in the network whereas the *action graph* is specific to the particular collaborative activities that the nodes perform and determines the desired collaboration activity. We consider a challenging question: Given a preferred emergent behavior, which connectivity and communication graphs can satisfy the requirements given by the corresponding action graph?

We have considered top-down as well as bottom-up approaches to this problem. In the top-down design, an optimization framework is developed that outputs efficient topologies given a single performance metric. Given different performance metrics, graphs that satisfy a favorable trade-off are selected as the candidates for the system structure. The focus of the bottom-up approach has been to discover how local preferences and decisions will result in the emergence of real world networks with certain requirements. Motif-based topology design is proposed in this framework. The designed links are realized via low power wireless media. The lower level design addresses challenges emanating from realizing the ideal graph topologies and consists of physical layer, MAC layer and network layer constraints. In order to design realistic and efficient networks, we have considered the interdependence of these two levels of design and develop a framework to capture the design requirements effectively.

To design efficient local connectivity patterns, we have used the idea of network motifs, which was first proposed in the context of biological networks. Network motifs are task specific local connectivity patterns, which exist with much higher frequency in real biological networks compared to those in random networks. These are sub-networks of low number of nodes (usually 3-4) whose persistence in networks performing similar tasks in different contexts, imply their efficiency in the sense that they optimize certain performance metric in a local scale. We use a simulation test bed to find network motifs for local level communication structures in a collaborative vehicles framework. Here, the group mission consists of several tasks that the agents participate in. The tasks include search operation, data gathering/processing, target finding and leader follower explorations. Each task gives rise to certain motifs that are specific to that task and the partial knowledge of the environment specifications that the agents operate in. In this way, given the subtasks that are necessary for the mission accomplishment, the most efficient task-specific local topologies are extracted. Switching suitable graphs when the mode of operation is changing can be handled by solving the resulting reachability problem using methods for symbolic planning such as graph grammars. Based on such switching, we also address the effects of split/merge operations on the spectral characteristics of the resulting connectivity graphs.

This work is a continuation of our previous research; some of our previous research results have been published and presented at the following:

J. S. Baras, P. Hovareshti and H. Chen, "Motif-based communication network formation for task specific collaboration in complex environments", to appear, *Proceedings of American Control conference (ACC 2011)*, 2011.

J. S. Baras and P.Hovareshti, "Efficient Communication Infrastructures for Distributed Control and decision making in Networked Stochastic Systems", *Proceedings of the 19th International Symposium on Mathematical Theory of Networks and Systems*, MTNS 2010.

Hua Chen, Pedram Hovareshti and John S. Baras, "Opportunistic Communications for Networked Controlled Systems of Autonomous Vehicles", *Proceedings of IEEE Military Communications Conference (MILCOM)*, 2010.

J. S. Baras and P. Hovareshti, "Efficient and Robust Communication Topologies for Distributed Decision Making in Networked Systems", *Proceedings of the 48th IEEE Conference on Decision and Control*, 2009.

P. Hovareshti, J. S. Baras, and V. Gupta, "Average Consensus over Small World Networks: A Probabilistic Framework", *Proceedings of the 47th IEEE Conference on Decision and Control*, 2008.

J. S. Baras and P.Hovareshti, "Effects of topology in networked systems: Stochastic Models and Small worlds", *Proceedings of the 47th IEEE Conference on Decision and Control*, 2008.

P. Hovareshti, and J. S. Baras, "Consensus Problems on Small World Graphs: A Structural Study", *Proceedings of the 2006 International Conference on Complex Systems*, Boston, Massachusetts, May 28-31, 2006.

ACKNOWLEDGMENT

Research is partially supported by the U.S. Army Research Laboratory Collaborative Technology Alliance on Micro Autonomous Systems and Technology (MAST) through BAE Systems award No W911NF-08-2-0004, and by DARPA under award number 013641-001 for the Multi-Scale Systems Center (MuSyC), through the FRCP of SRC and DARPA.