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A self-organisation framework for load balancing in adaptive networks

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ABSTRACT

The main point of this paper is to present how a generalised self-organisation framework can lead to a higher performance within adaptive networks. We take a simple example in the distributed task allocation to explain this framework, where each agent and its neighbourhood form a local network. The whole system is built up by many localised components, whose performance is highly influenced by the interdependent network structures. The basic queuing theory concepts are adopted to characterise the function of the agents, where they send and receive tasks locally. Through the load flow-in and flow-out, an adaptive control mechanism is applied to learn the rewiring parameters continuously. After that, a universal energy-based Metropolis rewiring method is used to quantify the structure adaptation, driving the network to a favourable one. This function-learning-adaptation (FLA) framework is implemented by the agents in a local, informative and quantitative manner, which can be widely used in many real-world applications.

1. Introduction

Consider the costs for communication and synchronisation, it is very difficult to organise the networked system under a centralised mechanism, especially when the size of agents is quite large. Effective structures fostered by local interactions known as *self-organization* [1] can lead to higher organization performance, which is widely observed in biology, chemistry, cognition, economy and sociology [2]. In nature, for example, the flocking behaviour of fish, birds, ants etc. can organize themselves in a local manner to form a robust structure, which is able to survive and self-repair from accidental perturbations. Therefore, the self-organisation framework implemented by the agents in the field of multi-agent systems (MAS) may lead to a fantastic outcome. Generally speaking, these systems should be able to work under some local rules to achieve global goals.

It is known that many real-world systems are demonstrated in the form of complex networks, where the nodes are connected by interacting links. Under bottom-up emergence, small-world networks [3] and scale-free networks [4] are well known self-organising networks in practice. Adaptive networks [5] are ubiquitous in modelling dynamical process in socio-technical systems, where the dynamics *on* the networks and the dynamics *of* networks are entangled tightly with each other. The first line of the dynamics lies in the evolution of individuals' states, while the second line of the dynamics focuses on the adaptation of structures. The related studies for adaptive networks can be found in a variety of fields ranging from voter model [6,7], network synchronisation [8,9], epidemics propagation [10,11], evolutionary games [12–14] etc. In particular, the evolution of cooperation is intensively reported in [15,16], and a large number of investigations [17–20] are explored to resolve the evolutionary dilemmas by dynamical linking.

In order to reveal the interdependence between structural behaviour and functional behaviour, one can consider the adaptive network model in multi-agent systems. In realistic

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situations, the performance of a networked agents system is highly dependent on the interacting structures, which influence the agents' states directly. To better understand the co-evolutionary dynamics in distributed organisations, we design a universal load balancing framework for the distributed MAS embedded into a network. Based on local information and decentralized control, this framework can be re-usable in many realistic situations, such as task allocation [21,22], power grids [23], wireless networks [24], traffic routing [25,26], packet delivery [27] etc. In all these systems, the congested networks or traffic jams caused by inefficient structure are frequently observed, which can be balanced effectively through some "soft" routing strategies and "hard" adaptation strategies [28]. In this paper, we will mainly investigate the network adaptation process in congested scenarios, where an example of task allocation is taken to illustrate the self-organisation mechanism.

From a more generalised perspective, the agents organized as a structured population are required to implement the global goals, where the spatial structures have a big influence on the organisation performance. Organisation performance is usually reflected by the overall functionality of the multi-agent system, which can be improved by structure adaptation. It is the feedback from the change of organisation performance that enables the agents to learn and find more effective parameters used for the network adaptation. The above process is called *function-learning-adaptation* (FLA) framework, aiming to improve the organisation performance through an intelligent, quantitative and decentralized adaptation strategy. Fig. 1 shows the schematic procedures of the FLA framework in dealing with the distributed problems for multi-agent system.

In the following, we will present how the FLA frame works for the distributed task allocation problem. The structure of the paper is organized as below: we describe the distributed task allocation model in Section 2, where the basic concepts of the model are defined. In Section 3, we shows how the FLA framework is constructed, followed by an example in Section 4. Based on the FLA framework, a transition from congested state to free-flow is obtained.

2. Network load flow

Large-scale distributed systems embedded into different kinds of networks have been investigated extensively for the last two decades. We can find various examples in Internet, P2P networks, and large supply chains, where (information, commercial, tasks) packets flow on those links. With the rapid development of networked communication systems, both the network size and the traffic intensity are growing quickly. As a result, the network congestion occurs frequently, where some nodes are overloaded but some are free. In the following, we will introduce a related load balancing problem in the distributed task allocation model.

As usual, we have a set of agents N, where for $\forall u \in N$, we let $NB(u)$ be the set of nodes which are the neighbours of u. Those agents are connected by a set of edges $M = \{u - v | u \in NB(v) \wedge v \in NB(u)\}$.

Each agent in the system is considered as a task sender as well as a task receivers, which means that the agent can deliver its tasks to its neighbours, meanwhile that agent should help to do the tasks allocated by its neighbours. In a generalised setting, tasks are generated at a rate $\lambda : N \to \mathbb{R}$ for the agents at each step, which is known as the arrival rate in

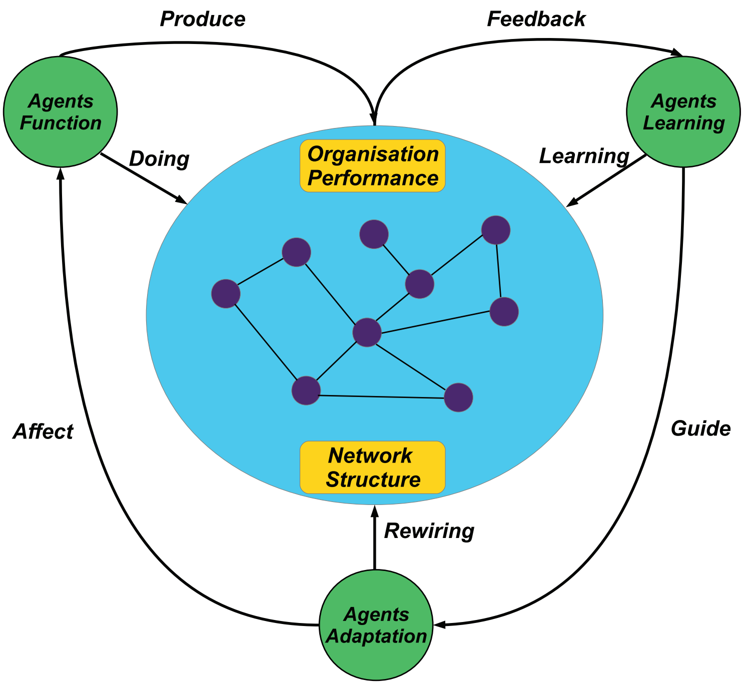

Fig. 1. Function-learning-adaptation framework in distributed MAS. In the structured MAS, the agents function together with network structure produce a certain organisation performance, which will provide feedback in the learning process to find a better solution for the network adaptation.