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Self-organizing Coalition Formation based on Non-cooperative Games in Social Networks

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Abstract. In multi-agent systems, the individual agent must form coalitions to accomplish complex tasks. However, the centralized management model is not flexible in a dynamic environment. To overcome the restriction caused by central control, the paper presents a self-organizing dynamic coalition mechanism based on game theory. Firstly, we adopt a distributed network to communicate among agents, allowing agents to solve the real-time task assignment problem autonomously. Next, a non-cooperative game negotiation model is introduced to find the optimal strategy for each agent. Finally, the effectiveness of our mechanism is validated by comparing it with the traditional command model in three distributed networks. Experimental results indicate the proposed mechanism is capable to improve the system utility.

Keywords: self-organization; coalition formation; multi-agent system; game theory.

1. Introduction

Nowadays, real-world applications have been extensively modeled by multi-agent systems, such as business management [1], emergency management [2] and military operations [3]. Many of the applications in multi-agent systems adopt the traditional command model. This model has many drawbacks, such as the complicated plan generation, the less complete information required and the difficulties in discovering and eliminating conflicts. Moreover, the centralized command model is challenging to adjust, which is not conducive to responding to unexpected situations. Thus, autonomous cooperation among agents is necessary for the success of execution tasks. Obviously, a centralized approach is not feasible in those systems.

In order to better solve the problems associated with the centralized command model, there is an urgent need for these systems to be autonomous and self-managing. The reason is that self-managed systems be able to save human management time and respond to emergencies [4]. Kota et al had come up with a view that any self-organizing system should possess three characteristics, namely only internal control, dynamic and continuous operation and no central control [5]. Thus, the nature of self-organization has attracted researchers' interest in addressing uncertainty and dynamic demands in distributed and complex systems. Serugendo et al concluded the concepts and properties of self-organization in multi-agent systems [6]. In [7], the essential aspects of self-organization were discussed. The authors listed the main applications of three major artificial life domains. We can see that most of the research focuses on the concept and application of self-organization. In practice, spontaneously organizing teams to execute elaborate tasks adopts the method of coalition formation.

In recent years, there has been significant development of research in the field of dynamic coalition formation [8]. Most of the research focuses on finding an optimal coalition under a fully connected structure. However, given the time constraints and complexity of the calculations, it is impractical to assume that each agent considers forming coalitions with all other agents. These problems have been noticed by many researchers and they have proposed a number of approaches to deal with them. Gaston et al discussed the impact of different network structures on the formation of coalitions by agents [9]. This research created new ideas for coalition formation.

On the other hand, a crucial cooperative model in the field of coalitional games is coalition formation [10]. Moreover, the study of self-organization needs fair and reasonable distribution

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principles and corresponding incentive mechanisms. Before forming a coalition, the rational agents are independent and belong to a non-cooperative relationship. The task initiator invites agents through an offer and encourages the system agents to join the coalition through the reward of executing tasks, which can accomplish the synergistic cooperation of different agents. The process of forming coalitions by self-organization is actually a potential game process. In their studies, distributed collaborative strategies and algorithms were proposed based on game theory [11]. Xie et al studied the problem of dynamic task assignment under distributed multi-agent responsibilities, and a Bayesian game is introduced to form overlapping coalition games in a constrained communication network [12]. Although the approach reflects the autonomy of agent network reconfiguration, it ignores the communication cost between agents. Therefore, game theory is a sound theoretical approach to studying the above problems.

Based on this background, we study the problem of self-organizing coalition formation in the multi-agent system. A negotiation mechanism based on a non-cooperative game is designed to solve real-time tasks. The rest of the paper is organized as follows: In the "Agent Network Model" section introduces relevant concepts in the model. The "Self-organizing Coalition Formation" section introduces the process of negotiation and coalition formation. The "Experimental Analysis" section employs algorithmic simulation to analyze the results in comparison with other mechanisms. The article is concluded in the "Conclusion" section.

2. Agent Network Model

For multi-agent systems, reliable communication ensures that agents cooperate to complete their tasks. In this paper, a social network is used for agent communication. As shown in Fig.1, it is a network structure based on neighboring nodes. It is defined as

Definition 1 (Social network). Each social network $AE = \langle A, E, D \rangle$ is a graph composed of a set of interdependent agents in which the agents are connected to each other by a weighted undirected line. Where A is a set of autonomous agents $A = \{a_1, a_2, ..., a_n\}$, and E is the set of links between agents, $E \subseteq A \times A$. If $\langle a_i, a_j \rangle \in E$, it means that a_i and a_j are neighbors and can communicate, and the $d(a_i, a_j)$ is the weight that represents the communication cost between a_i and a_j on the links. E is symmetric and reflexive.

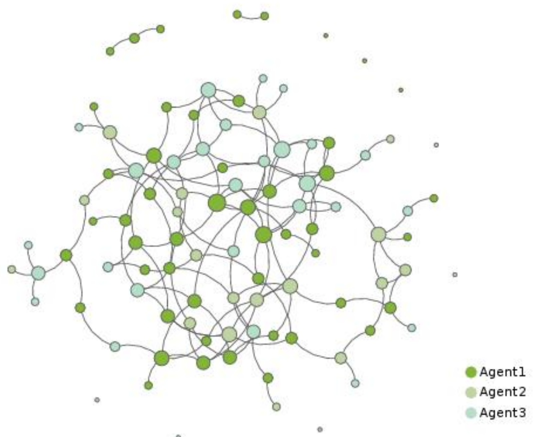

Figure 1. Neighborhood network

When Assume that there are k resources available in the whole system, $R = \{r_1, r_2, ..., r_k\}$. For each agent a_i in the network, a quadruple $\langle r_{a_i}, N_{a_i}, Cr_{a_i} \rangle$ can be used to describe its characteristics,

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where $r_{a_i} \subseteq R$ is a_i contains resources, and N_{a_i} contains the neighbors of agent a_i. Cr_{a_i} is the cost of each resource provided by a_i.

We consider a set of tasks $W = \{w_1, w_2, ..., w_q\}$, for $w_1 \in W$, it is represented by a tuple $\langle R_{w_i}, Pa_{w_i}, B_{w_i}(t) \rangle$, where $R_{w_i} \subseteq R$ is the resource demand of task w_i, and Pa_{w_i} indicates the location of task w_i. $B_{w_i}(t)$ is a function of complete time t, which is the payoff of completing task w_i. The earlier task w_i is completed, the more the payoff will be.

Definition 2 (Coalition). In an n-player game, the set of players is indicated by $A = \{a_1, a_2, ..., a_n\}$, and any subset c of A is called a coalition, i.e., for $\forall c \subseteq A$, the empty set and the whole set can also be viewed as a coalition. Where c denotes a group of agents. These agents intend to cooperate for a common task, each coalition corresponds to a specific task. In other words, $C = \{c_1, c_2, ..., c_q\}$ is a set of coalitions, which are related to a set of tasks $w_1, w_2, ..., w_q$, respectively. Each coalition $c_i \subseteq C$ is composed of a tuple $\langle A_{w_i}, F_{w_i} \rangle$, where A_{w_i} is a set of agents joining coalition c_i. F_{w_i} is the resources contributed by agents in coalition c_i.

The coalition formation problem in $CF-AE$ must satisfy the following conditions. For task w_i, only agents associated with Pa_{w_i} can join the coalition. In order to form an effective coalition, the resources required by the task w_i must be provided in full by the agents in the corresponding coalition, i.e., $\bigcup_{a_i \in c} r_{a_i} \supseteq R_{w_i}$.

Based on the above social network, the agent detects tasks in real-time. For the tasks randomly released in the system, agents can respond intelligently and form the corresponding coalition to execute the task. According to game theory, the process of self-organizing task allocation can be modeled as a coalition formation game in a multi-agent system. $G = \langle A, R, S, \mathrm{u} \rangle$

where:

A is a collection of agents, i.e., $A = \{a_1, a_2, ..., a_n\}$.

R is a collection of resources, i.e., $R = \{r_1, r_2, ..., r_k\}$.

S is a collection of strategies that agents to allocate their resources to different coalitions.

u represents a utility function.

Coalition characteristic function is $\mathrm{v}: 2^A \to \mathbb{R}$ that maps each possible coalition to the real number $\mathbb{R}$, describing how much collective payoff a certain number of agents can obtain through forming the coalition c_i undertaking task w_i. Therefore, this coalition value function can be defined as

$$V(c_i, w_i) = B_{w_i}(t) - WCC(c_i) - WRC(c_i) \tag{1}$$

where task w_i initiators' total communication cost WCC is incurred by necessary communication with other agents, which is given by $WCC(c_i) = \sum_{a_i \in c_i} d(Pa_i, a_j)$, the total resource cost WRC when the coalition completes task w_i, which is given by $WRC(c_i) = \sum_{a_i \in c_i} F_{w_i}(a_i, r_l)$.

3. Self-organizing Coalition Formation

In social networks, the decision-making process of agents is independent and autonomous, and the decisions are based on incomplete information. We assume that agents are rational and self-interested, try to maximize their payoff, and choose coalitions according to their preferences. Before describing coalition formation, we need to propose a definition of the three roles of the agent.

Definition 3 (Initiator, respondent, freelancer). The agent that initiates a task is called an initiator, which initializes the task information and publishes the relevant task coalition formation

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information to its neighbors, and the agent who receives task information and agrees to join in the coalition is called a respondent. The rest of the agents all become freelancers.

Since we assume that agents can only communicate with their neighbors, we define a set $Z = \{Z_1, Z_2, \ldots Z_n\}$. Where Z is a relational linkage between agents and part of the set E , i.e., $\bigcup_{1 \le i \le n} Z_i = E$ and $\forall Z_i, Z_j \in Z : i \ne j \Rightarrow Z_i \cap Z_j = \varnothing$. Z_i seems to have the same meaning as N_{a_i} , but Z_i represents not only a_i 's neighbors but also other agents that will be indirectly connected to a_i in future coalition formation. N_{a_i} represents only a_i 's the direct neighbors.

For each task w_i , it is initiated by a free agent Pa_{w_i} with a certain probability. Before the task w_i deadline, the initiator Pa_{w_i} will check whether the resources of its neighbors, including itself, can meet the task resource requirements. Firstly, Pa_{w_i} contributes its resources to task w_i , if any neighbors agent can satisfy the demand of task w_i , then Pa_{w_i} will negotiate with neighbor a_j to sign a contract on resource contribution. If a_i 's resources still cannot satisfy the demand of task w_i , considering the time limit of task w_i and their respective payoff. Neighbors in a dynamic environment will spontaneously find their neighbors to negotiate with Pa_{w_i} again (Acquaintance effect). This indicates that Pa_{w_i} can only select coalition members from the set Z_i , which consists of a_i 's neighbors and their neighbors. (The negotiation mechanism will be described in the following section) If Pa_{w_i} has recruited all agents that meet the resource requirements of task w_i , the coalition construction will terminated. The coalition is formed.

3.1 The negotiation protocol

The agent negotiates via a social network to complete the coalition formation. The negotiations focus on a single problem: the contribution of resources by a respondent or a freelancer joining a coalition initiated by the initiator. The basic idea stems from bargaining in game theory, where both sellers and buyers can make optimal choices within their own choice for achieving overall resource optimization.

Definition 4 (Resource status). There are three statuses of resources in the network. A resource can only be in one of the three statuses at any time step. As shown in Figure 2, when a task is initiated, or a coalition is formed successfully, the status of resources is busy, and when a coalition lacks all the resources needed to complete the task, or the coalition has not performed the task, the status of resources are waiting. The resources of agents who have neither joined in any coalition nor initiated a task in free status.

The negotiation process is divided into two main stages of the game. The first stage is a game between the initiator and the other agents with the maximization of their respective payoffs as the objective function. The agent adjusts its strategy through the initiator's strategy.

Offer[O] After an evaluation, the task initiator proactively sends an offer to its neighbors regarding the task's resource requirements and time urgency. However, we discuss the initiator's expected payoff before the offer. Due to the dynamic and uncertain nature of social networks, many factors will affect the expected payoff.

Respond[R] Since different resources status will result in different response strategies, the respondents or freelancers needs to consider the status of resources before replying to the initiators.

- Agents with free resources will accept the offer immediately because joining in a coalition to perform a task will gain a certain amount of payoff, which is the best strategy for comparison with no payoff.
- The agents who own the resource have already joined a coalition c_k . When it receives a new offer, it will face a dilemma (whether the resource stays in the original coalition or accepts the new offer). According to its preferences, any choice is based on maximizing its payoff.

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At this point, agents enter the second stage of the game because the payoff of tasks gradually decreases with time, where the goal of the competing parties is to maximize the global utility.

Once all agents that can satisfy the task resources are recruited in the coalition and no resources have been exited, the task will begin to execute. During the execution of the task, no agent can leave the coalition until the task is completed.

4. Experimental Analysis

Do In this section, a series of simulation experiments are conducted to verify the performance and effectiveness of the proposed mechanism. Firstly, we describe the experimental parameters set-up, and then analyze and discuss the experimental results.

4.1 Experimental set-up

To objectively display the performance of the proposed mechanism, named self-organizing coalition formation (SOCF). We compare SOCF with the traditional command model (TCF). Moreover, three different structural network models are adopted to model our social networks, the Scale-Free networks [13], the Random networks [14] and the Small-World networks [15].

4.2 TCF mechanism

this mechanism was created by us to simulate the traditional command and control model in reality. High-level managers receive tasks and generate action strategies through planning, which are then cascaded to lower-level agents. Its main feature is the cascading of tasks and the time-consuming deployment process. The use of this mechanism better reflects the importance of edge self-organization due to the over-reliance on management deployment.

The values of the relevant parameters used in the experiments and their mathematical meaning are described in Tab.1. To achieve statistical significance, the results of each experiment are obtained by averaging 30 runs. In our experiments, we employed the system utility to verify the efficiency of the two mechanisms. It is defined as

$$U(C)=\sum_{i}^{q}V(c_i,w_i)\ . \tag{2}$$

Table 1. PARAMETER SETTING

Parameter	***value***
N	[200,450]
W	[10,35]
R	15
r_{a_i}	[2,8]
R_w	[3,15]
Cr	[1,10]
d	[1,10]

4.3 Experimental results and analysis

In the experiments, the impact of the number of agents in three different networks on the algorithm is studied. In Fig. 2, the number of tasks is fixed at 20, and the number of agents varies from 200 to 450. From the results, we can find that the system utility of SOCF in various networks is significantly higher than that of TCF. The cause of this phenomenon is that with the increase of the number of agents, the more neighbors, the greater the likelihood of completing the task. However, the system utility of SOCF is significantly higher than the TCF mechanisms. This is because the TCF mechanism consumes a lot of time in the command process and thus has relatively low system utility. The SOCF uses edge agents to autonomously form coalitions to perform tasks,

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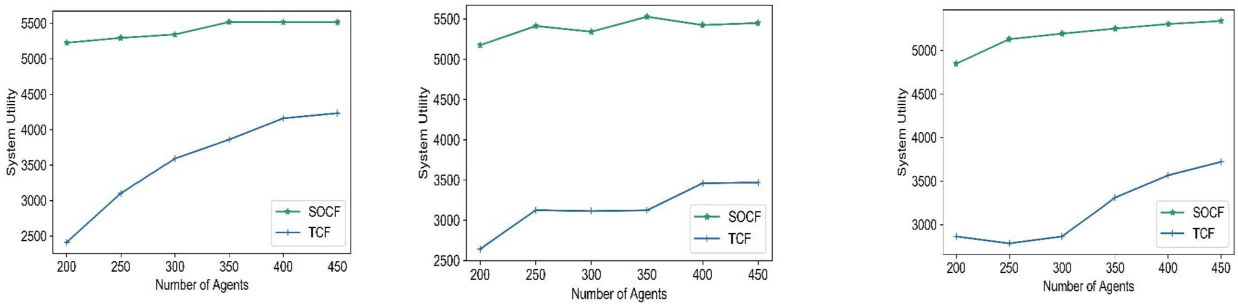
saving the time to form coalitions. In conclusion, when there are enough neighbors, the initiator has more resources to deal with its task.

5. Conclusion

In this paper, we provided a self-organizing coalition formation mechanism based on game theory, which is suitable for interconnecting agents in social networks. The agents dynamically adjust their participation in different coalitions according to their preference relations. We consider the acquaintance effect to allow neighbors to bring their neighbors into the coalition. In particular, we capture the nature of agent self-interested, and a non-cooperative game negotiation model is built. It is a practical application compared to the traditional models with cooperativeness assumption. Finally, a series of experiments are carried out to verify the effectiveness of the proposed mechanism and compared it with the TCF mechanisms. The results show that among the three social networks, the SOCF mechanism has shown better performance in improving system utility. At the same time, the mechanism also provides theoretical guidance for emergency management and business management in the real world. As Figure 2 Shows.



(a) the Random network (b) the Small-World network (c) the Scale-Free network

Figure 2. System utility of two mechanisms in three different networks.

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