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Social Organisation of Mobile Sensors for Wildfire Spread Estimation

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Abstract: In this paper, we focus on social organisation of mobile sensor network for the observation of distributed parameter systems. We built a framework that allows us to compare different social organisation in terms of observation performance. First, we studied the topology of generic social organisation with graph theory criteria. Then, we benchmarked some of these organisations when we applied them to mobile sensor network for the observation of a cellular-automaton simulated wildfire.

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Keywords: Forest Fire Spread Dynamics, Mobile Sensors, Multi-agent Systems, Cellular Automaton, Distributed-Parameter Systems, Observers.

1. INTRODUCTION

In 2017, over 2300 fires started in the French Mediterranean area¹. About 200 km² of forest was destroyed by these fires. Of all these, only 10% were detected by watch-towers or patrols, which makes it possible to act quickly. The presence of more detection systems and/or the use of new technology could make it possible to act quickly on the outbreak of fires and thus reduce the damage of forest fires. The use of mobile sensor networks could compensate for this slow detection of forest fire outbreaks.

As the fire spreading is a spatio-temporal phenomenon that interact with its environment, it can be studied as a distributed parameters system (DPS) in terms of inputs and outputs. Such systems have been usually modelled by means of partial differential equations (PDEs). However when dealing with complex ecological systems that are generally non linear, stochastic and multi-scale multi-physics, the usual PDEs cannot provide a realistic and appropriate modelling tool. Moreover, efficient implementations of these models is often very challenging because of the strong non linearities of these equations and the problems raised in their discretization because, in many cases, energy conservation is not respected which makes the model erroneous.

Cellular automata (CA) may thus be considered as discrete idealisations of PDEs and can be used to represent these DPS CAs are already distributed in space, which gives them an advantage over DPS modelling. In addition, a CA uses the local equations of physical systems, which are usually easier to discretize than the global equations. Over the years, CA have been applied not only to model general phenomenological aspects of the world, including communication, computation, growth, reproduction, but

also to be used as an alternative to model and simulate large-scale systems where partial differential equations (PDE's) involve complex and computationally expensive simulations

Sensor networks have been studied for years but the increasing number of sensors makes them an even more important issue today. The use of sensor networks to observe DPSs poses problems in the recovery and placement of sensors. These problems are considered as NP hard (Meguerdichian et al., 2001; Han et al., 2008) but there are some algorithms that propose solutions. However, when sensors are able to move, the problem becomes even more complicated, there are very few algorithms to solve mobile sensor network problems (Demetriou, 2010). Our approach is based on the multi-agent paradigm, which describes that each sensor makes decisions based on the environment and on the communication with other sensors. The organisation of a multi-agent system is similar to the social organisation of our society, agents have different roles in this organisation and communicate to achieve their personal goals that satisfy the overall goal of the system (which is often unknown to agents). As the mobile sensor network becomes a multi-agent system, we will no longer talk about a mobile sensor but simply about an agent.

In this paper, we present our work on comparing the performance of various social organisations of mobile sensor network for dynamic system observation. This study is based on the results of a previous study on decentralised estimation of forest fire spread, see Schlotterbeck et al. (2018). This study explained that cognitive agents have better observation performance than others, these agents carry a model of the system they observe and they are able to communicate with each other. In our study, we will focus on the communications of these agents and more particularly, the social organisation of the network. Our goal is to create a framework that will allow us to evaluate the advantages and disadvantages of different sensor net-

¹ <http://www.promethee.com>: Prométhée is the official database for forest fires in the French Mediterranean area. Since 1973, this database has reported all forest fires in this area.

work organisations. We will start by presenting the forest fire model we have chosen. Then, we will present different social organisation schemes that we will classify according to four criteria derived from graph theory. Afterwards, we will present the observation algorithms of the sensors and their communications. Finally, we will run simulations with different social organisations and for different numbers of sensors in each organisation to see the differences in performance of mobile sensor network organisations.

2. DISTRIBUTED PARAMETERS SYSTEM MODEL

To simulate the spread of forest fire, we will use the model defined in (Schlotterbeck et al., 2018) which uses the definition of the El Yacoubi cellular automaton and the results of Green, see El Yacoubi (2008); Green (1989). This model of forest fire is a class 1 cellular automaton (Wolfram, 1984), i.e. once the forest has burned, it does not burn again. We have therefore added an artificial regrowth which aims at creating oscillating and/or chaotic phenomena (which will be a class 2 or 3 cellular automaton), depending on the value of the parameters we use.

The mobile sensors do not embed the forest fire model because we want our benchmark to be independent of the application. In their observation task, mobile sensors use another model that don't take into account system dynamics but only observation dynamics such as: elapsed time since last measurement and change in cell's state. Each mobile sensor of the network has an internal model of the system, this model is called *observation CA* (in opposition to the wildfire CA). The observation CA is defined by the quadruple $\mathcal{A} = (\mathcal{L}, \mathcal{S}, \mathcal{N}, a)$ where:

- \mathcal{L} is the same lattice as for the wildfire CA.
- \mathcal{S} is a discrete composite state set: $S = \mathbb{N}^3$. Its sub-states are:
 - $s^A \in \mathbb{N}$: Time elapsed since last measurement.
 - $s^U \in \mathbb{N}$: Uncertainty of the cell.
 - $s^{Ch} \in \mathbb{N}$: Status of the cell (*i.e.* if the cell has changed between the last two measures).
- \mathcal{N} is the neighbourhood and has a distance of 0, *i.e.* $\mathcal{N}(c) = \{c\}$. This CA has no neighbourhood because it has no spatial dynamics. Wildfire dynamics are not reproduced, only the state of the system is measured and then stored in this CA.
- a is the transition function, described below.

When a mobile sensor is above a zone, it sets the last measurement time s^A and the uncertainty s^U to 0, and looks at whether the state of the observed cell has changed, *i.e.* if the state of the cell in the wildfire CA has changed. The sensor does this for all the cells it can observe. For cells that it cannot, the last measurement time is incremented for all cells and the uncertainty which is incremented if and only if the cell has previously changed state ($s^{Ch} = 1$).

In order to evaluate the performance of the sensor network, we use an oracle that merge data from all the sensors. Then, we calculate the *distance* between the state of the "real", CA-simulated system and that of the oracle. To merge data, the oracle, for each cell, takes the state from all sensors and select the most recent data, *i.e.* the one that has the lowest time since the last measurement, s^A .

This centralised, oracle-built state is not accessible to the agents and only used for evaluation purpose.

To calculate the distance between the real system and the oracle system we will use equation (1) where s is the state of the real system, \hat{s} the state of the oracle system, and d is defined by (2).

$$D(t) = \sum_{c \in \mathcal{L}} d(x_t(c), \hat{s}_t(c)) \quad (1)$$

$$d(s, s') = \begin{cases} 1 & \text{if } s \neq s' \\ 0 & \text{else} \end{cases} \quad (2)$$

3. SOCIAL ORGANISATION CLASSIFICATION

The social organisations of multi-agent systems can take two main forms, explicit and implicit organisations (Ferber et al., 2003; Serugendo et al., 2003). Implicit organisations are achieved through local interactions between agents, such as relationships on social networks, while explicit organisations are achieved by designers, such as the organisation chart of a company. We will try to classify different explicit organisations inspired by the sociology of organisations (Horling and Lesser, 2004).

In order to compare different social organisations in the observation task, we wanted to make sure that we cover a diverse sample of social organisations. To discriminate social organisations we chose to consider their similarity with a hierarchical organisation.

Krackhardt proposes in (Krackhardt, 2014) four criteria for numerically assessing whether a graph is an out-tree. In organisational topology, the hierarchical organisation can be represented by an out-tree. So by using these four criteria, we can classify organisations according to their degree of hierarchy (or *hierarchiness*).

3.1 Social Organisation & Topology

Horling and Lesser have compiled in (Horling and Lesser, 2004) a list of social organisation used in multi-agent systems. These organisations are inspired by human organisation and are adapted for multi-agent systems. In their paper, Horling and Lesser present nine social organisations, we decided to study the hierarchical, federated, coalesced, and matrix organisations. The others are similar in terms of topology (congregation) or do not have a proper topology (team).

Hierarchical Organisation A hierarchical organisation is a type of organisation that is frequently found in our society, especially in corporate and military organisations. Its functioning is called "top-down": the leader makes decisions in broad terms and delegates the work to the agents below. These agents may themselves delegate to other agents below, if it's not the last agent in his branch. This organisation is quite simple to operate at has proven its worth in our society and in multi-agent systems (Juziuk et al., 2014).

The topology of a hierarchical organisation is an out-tree (or a rooted tree), which is why we used the criteria provided by Krackhardt.

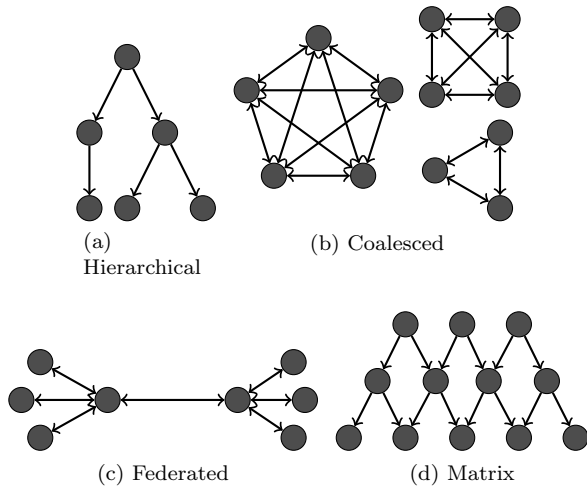


Fig. 1. Example topologies of organisation

Coalesced Organisation A Coalesced organisation is made up of one or more coalitions. A coalition is a group of agents which have come together for a common purpose which is a short-term goal. Coalitions act independently and without interactions. In a coalesced organisation, the coalitions have relatively short lifespans because when agents no longer have the same purpose, the coalition is dissolved. Thus, the links between agents are dynamic and evolve rapidly. Moreover, the agents of a coalition act in a selfish way, they will not help their comrades if they do not derive a direct benefit (exchange of information, services). The congregation is similar to the coalition but the agents have long-term goals in the organisation.

The Coalesced organisation has a graph that is not connected but is complete, so the topology is a disjoint union of complete graph.

Federated Organisation A federated organisation is made up of one or more federations. A federation is a group of agents who have delegated their sociability to a representative, in this way the agents of a federation communicate only with their representative even if the latter is not the target of the request. For example, if an agent of the federation wants to communicate with another agent (whether in the same federation or not), he must communicate with his representative and it is the latter who will act as the intermediary in this communication.

The graph of a federated organisation can be seen as a set of 2 levels rooted trees where roots form a complete graph.

Matrix Organisation A matrix organisation is similar to a hierarchy, each agent obeys its superior and can give orders to its subordinates. In a matrix organisation, an agent may have several superiors called "influencers". This scheme makes it possible to have several managers with several different objectives, these managers can, through this organisation, access the same agents.

3.2 Classification Criterion

The four criteria provided in (Krackhardt, 2014) are: *Connectedness*, *Hierarchy*, *Graph Efficiency*, and *Least-Upper-Boundedness*. They are both necessary and sufficient con-

ditions for the graph to be an out-tree. They are evaluated between 0 and 1 and thus make it possible to see if an organisation is close or not to a hierarchical organisation.

Connectedness is used to assess whether an agent can communicate with another, directly or through other agents. This criterion is close to the notion of connection in graph theory: if the graph is connected then its connectedness is 1 but brings more nuance if it is not.

If the graph is not fully connected ($connectedness < 1$) then there are several subgraphs that are connected, these graphs are called components of the graph.

Hierarchy uses the direction of the directed graph to define hierarchical superiority. Krackhardt defines this direction as: *for each pair of points where one can reach another, the second cannot reach the first*. In relation to social organisations, this criterion makes it possible to describe the fact that one agent is the "hierarchical superior" of another. One agent can give orders to the other but cannot receive them.

Graph Efficiency quantifies the number of redundant links to make a fully connected oriented graph. To connect N vertices it is necessary at least $N - 1$ edges. It is a question of evaluating, for each component, the number of redundant links.

Least-Upper-Boundedness (LUB) quantifies the proportion of agents who have a common ancestor. Two agents are said to have a common ancestor if and only if there is an agent (themselves or another) who can reach them both.

3.3 Evaluation of criteria

With the four criteria, we can assess how close the topology of an organisation is to that of a hierarchical organisation. To allow for a simple classification (i.e. with a single value) we will use a distance based on the four criteria. In an arbitrary way, we use the mean of the four criteria to evaluate hierarchiness.

Now that we have defined the criteria and topology of the organisations, we will be able to evaluate the four criteria for each organisation and their degree of hierarchy. To begin with, we can notice that for different topologies of the coalesced organisation, we have different values for the four criteria, e.g. fig 1 b) has a hierarchiness of $\frac{15}{44}$ ($c = \frac{4}{11}; h = 0; e = 0; l = 1$) and a fully-connected coalesced organisation has a hierarchiness of $\frac{1}{2}$ ($c = 1; h = 0; e = 0; l = 1$). Since organisations have criteria that can vary, we will use intervals for the value of the criteria.

To evaluate the extreme values of the criteria, we took extreme cases of topology, i.e. with connectedness equal to 0 or 1. With these extreme topologies, we are able to classify the organisations according to the different criteria, these results are summarised in Table 1.

Figure 2 presents the intervals of organisations' hierarchiness. We can see that the matrix organisation has a hierarchiness defined over a large interval, such that it overlaps with the other three organisations. The other three organisations cover a large span of the possible values, even

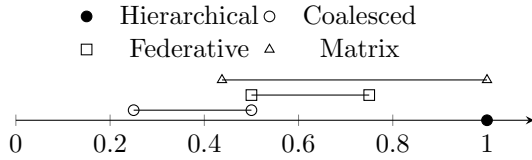


Fig. 2. Hierarchiness of organisations

if it lacks an organisation with a very low hierarchiness. That is why, for the rest of this study, we will focus on hierarchical, federated and coalesced organisations.

4. SIMULATOR

Now that we have classified the social organisations of the multi-agent systems provided by Horling and Lesser, we will be able to perform different simulations to see the differences in performance of these organisations for observing dynamic systems.

In the context of the multi-agent paradigm, we will describe the coordination protocol used in the implemented social organisations and the topology of their communication. We will then present the observation algorithms used by the sensors and we will end by describing the specific behaviours associated with the different organisations.

4.1 Coordination protocols

The Contract Net protocol Smith (1980) allows agents to collaborate using a decision process similar to an auction. In this process, some agents will offer contracts to other agents to carry out an action. In this protocol, there are 2 types of participants, the *sponsor* who creates the contract and the *contractors* who could perform the contract. To begin with, the sponsor issues a call for tenders to all agents who are likely to carry out the actions of the contract. Then, potential contractors calculate the cost associated with the contract and return these costs to the sponsor (if a contractor cannot perform the actions, it does not respond to the offer). After a certain period of time, the sponsor chooses the contractor with the lowest cost and sends it a confirmation. As soon as the confirmation is received, the contractor starts the execution of the contract.

4.2 Observation

Among all the observation agents, we will consider two types of agents, *explorers* which explore the system uniformly and *followers* which will look for areas that are changing (i.e. areas that are on fire or growing back). These two types of agents will have a similar observation algorithm except for the choice of the areas they observe. Explorers will seek for areas were duration since the last

measurement, s^A , is the greatest. Followers for areas with greatest uncertainty, s^U , which depends on the variability of the area.

Environment observation is conducted as follow: agents are responsible for the observation of a finite set of zones. The number of zones an agent can observe is determined by the *cost* of this observation which depends on the capacities of the agent (e.g. travel speed, sensors range). Zone attribution among agent is dynamic, done using the Contract Net protocol, and depends on the current social organisation. To choose which zone to observe, an agent calculate the average value of the cells' state (s^A or s^U depending on the type of agent) over each zone. The agent will move to the zone with the highest average value, then choose the cell with the highest value as the destination.

4.3 Cost Function

The cost function used by a contractor to calculate the cost to observe a zone. This cost is zero if the zone is already observed by this agent, otherwise it is expressed by equation (3) where \mathcal{A} is the area of the zone, d a distance between 2 zones, r the measuring range of the agent, S the set of zones already observed by the contractor, and z the contract zone.

$$f_{cost}(z) = \mathcal{A} \left(\bigcup_{S \cup \{z\}} s \right) + \max_{s_i, s_j \in S \cup \{z\}} d(s_i, s_j).r \quad (3)$$

4.4 Organisation

The main difference among social organisations in the observation task is which agents can offer contracts to others. The ability to initiate an auction will depends on the role of agents in the organisation. For example, in a hierarchical organisation, only the chief can give observation orders (i.e. create contracts) while in a coalesced organisation all agents can offer each other observation contracts.

Hierarchical Organisation We have chosen to implement a 2-level hierarchy. The first level is made up of the chief of the organisation and in the second level, there are 2 kind of agents, explorer and follower. The chief of the organisation is not an observation agent like others, its role is to lead the explorers and followers which are under its command. In this way, the chief is the only one who can create observation contracts.

Coalesced Organisation For the coalesced organisation, we have chosen to have a single coalition in which all agents can communicate with each other. Unlike other organisations there is no leader or representative, explorers and followers must communicate directly with each other. As there is no representative, the explorers will have to divide the exploration of the area without centralisation. The explorers will choose to explore the nearby areas and will create exploration contracts to distribute the areas among themselves.

Federated Organisation For the federated organisation, we split the group in two sub-groups and we therefore have two federations. The first is the federation of followers

Table 1. Classification of social organisations with the 4 criteria

Organisation	Connectedness	Hierarchy	Efficiency	LUB
Hierarchical	1	1	1	1
Federated	1	0	[0,1]	1
Coalesced	[0,1]	0	0	1
Matrix	[0,1]	1	$]\frac{3}{4}, 1]$	[0,1]

and the second is the federation of explorers. In each federation there are 2 types of agents, the followers (resp. explorers) and a representative. For each federation, the representative acts as a broker who manages the contracts and redistributes them to the concerned agents.

In the next section, we will specify in more detail the topology of the organisation by specifying the number of agents and their function.

5. PERFORMANCE ANALYSIS

We will now conduct observational simulations with the different organisations to see the differences in performance. We will run simulations on two scenarios: the first corresponds to the discovery of the environment and the monitoring of fire fronts.

5.1 Organisation

In order to evaluate the performance of agents, we will perform simulations for the three organisations we presented in the previous section but also for different numbers of agents. To increase the number of agents without changing the organisation's performance, we will reduce the speed and the measuring range of each agent. We will simulate with 8, 16, 24, and 32 agents, we will not add more agents because of the long simulation times. In each organisation, the number of agent managers will be fixed but the number of explorers will change according to the number of agents, since the individual observation performance of agents decreases. All other agents will be followers, so the coalesced organisation will have more agents than the other organisations.

5.2 Scenarios

Scenario 1: As the agents do not know the environment at initialisation, it is necessary for them to discover it by themselves. The purpose of this scenario is to highlight the performance of organisations that are effective in discovering the environment. For this purpose we will carry out a simulation without starting the fire and for a very short time.

Scenario 2: In this second scenario, we will evaluate the performance of organisations to monitor a single forest fire. The purpose of this scenario is to evaluate the performance of the agents in the case of wildfire monitoring and forest regrowth, i.e. a fire will start, then as soon as the forest has burned and regrowth.

Table 2 groups the simulation configurations of these two scenarios. All these parameters are expressed in number of iterations. *Duration* represents the total simulation time, *Ignition Time* represents the number of iterations before the first start of fire, and *Ignition Loop* represents the number of iterations between two starts of fire.

Table 2. Simulation configuration of the scenarios

Scenario	Duration	Ignition Time
1	300	None
2	900	200

5.3 Results

Scenario 1: Simulation results for scenario 1, environmental discovery, are depicted in Figure 3, which presents the observation error, $D(t)$ in eq. 1, as a function of time for the three organisations with 32 agents each. We note that hierarchical and federated organisations have similar results while the coalesced organisation has a steeper diminution of error over time. This difference is explained by the behaviour of the three organisations: organisations that have agents that act as "managers" (i.e. hierarchical and federated organisation) use it to make a centralised distribution of observation zones, whereas in the coalesced organisation, it is the observation agents who distribute the zones themselves, in a decentralised way. Agents in the coalesced organisation can start to observe zones immediately and autonomously whereas in the other two organisations, observer agents have to wait for their "manager" to request observations and to complete the contract net protocol to start observing. This difference in behaviour also explains the delay in federated and hierarchical organisations used to divide the observation areas. However, these two organisations have a greater convergence that reflects a better distribution of observation areas.

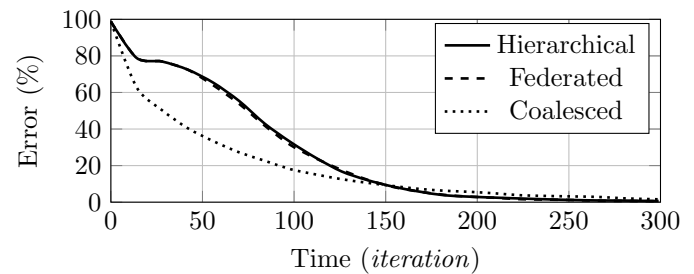


Fig. 3. Observation error during scenario 1, discovery of the environment, for 32 agents.

Scenario 2: Now that we have studied the discovery of the environment, we will study the monitoring of a wildfire. The observation error, presented in Figure 4, decreases rapidly during the first 200 iterations, which correspond the discovery of the environment. Then, the increase in error is due to the propagation of the fire (between 200 and 500 iterations): the wildfire CA state is constantly changing during this phase, making the error grow because the total area that can be observed by the agents is smaller than the area that is changing. Once the fire has burnt almost all the environment (after iteration 500), the wildfire CA state change rate lowers, making it possible for the agents to lower the error rate. In this phase, the performance gaps between the three organisations are not significant, reflecting that the organisation has little influence on observation performance.

5.4 Discussion

The main difference between the three organisation we were able to observe with our experiments concerns reactivity of the mobile sensor network to system change. Coalesced organisation is faster to construct an initial state of the environment, but is less effective than the others to do so. Once the initial state is built (i.e. during the

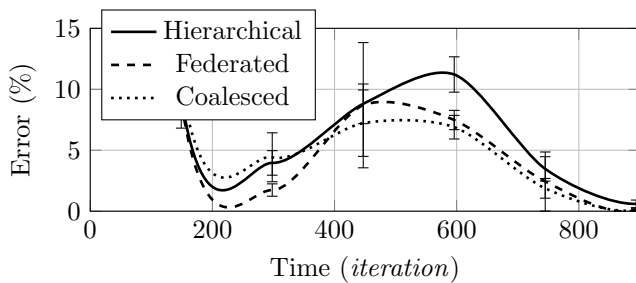


Fig. 4. Monitoring of wildfire spread for 8 agents.

observation phase), the difference between organisations in term of error rate are not significant. The only difference is in the reactivity of the hierarchy which starts to lower the error rate later than the two other organisations. We were able to establish that, in our setup, the organisation of the mobile sensor network has little influence on observation performance.

This simulator will allow us, in the future, to add constraints and defects in our organisations and evaluate their impact. Indeed, the three organisations are calibrated so that their observation performance is similar, so any difference between organisations following the addition of a constraint or defect will show the sensitivity and robustness of organisations regarding these constraints and defects.

6. CONCLUSION & PERSPECTIVES

This work presents a comparison of three social organisations of mobile sensor networks for the estimation of a wildfire spread. We first evaluated social organisations according to four criteria based on the corresponding underlying interconnection graph topology and then classified them according to their respective hierarchiness. Despite their differences, organisations have similar performance in wildfire observation simulations with respect to the estimation error. The first scenario highlights the discovery of an environment without spatial-temporal dynamics. We noticed for this scenario a better reactivity of the coalesced organisation due to its decentralisation. The second scenario allows the observation of wildfire spread dynamics. This lack of significant difference in error rates is the consequence of the choice to give identical behaviours to agents in the three compared organisations. The only differences between organisations are in the way agents allocate areas to observe among them. Positively stated, this negative result shows the lack of bias introduced in the behaviour of the agents for the proposed benchmark.

In a future work, we will focus on communication issues. We believe that they play an important role to distinguish the dynamical behaviour of the considered social organisations. We will first investigate the case of a mobile sensors network with limited range of communication. It is conjectured that this constraint will generate important differences with respect to the estimation error rates and deadlock situations. In addition, we believe that this limitation will affect all organisations but in different ways and to different extents, thus, some organisations will be more robust with communications limitations. The next step will be to detect such a deadlock situation and to

imagine decentralised mechanisms to change the social organisation of the sensors network when such deadlock appears.

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REFERENCES

- Demetriou, M.A. (2010). Guidance of mobile actuator-plus-sensor networks for improved control and estimation of distributed parameter systems. *IEEE Transactions on Automatic Control*, 55(7), 1570–1584.
- El Yacoubi, S. (2008). A mathematical method for control problems on cellular automata models. *International Journal of Systems Science*, 39(5), 529–538.
- Ferber, J., Gutknecht, O., and Michel, F. (2003). From agents to organizations: an organizational view of multi-agent systems. In *International workshop on agent-oriented software engineering*, 214–230. Springer.
- Green, D.G. (1989). Simulated effects of fire, dispersal and spatial pattern on competition within forest mosaics. *Vegetatio*, 82(2), 139–153.
- Han, X., Cao, X., Lloyd, E.L., and Shen, C.C. (2008). Deploying directional sensor networks with guaranteed connectivity and coverage. In *2008 5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, 153–160. IEEE.
- Horling, B. and Lesser, V. (2004). A survey of multi-agent organizational paradigms. *The Knowledge engineering review*, 19(4), 281–316.
- Juziuk, J., Weyns, D., and Holvoet, T. (2014). Design patterns for multi-agent systems: A systematic literature review. In *Agent-Oriented Software Engineering*, 79–99. Springer.
- Krackhardt, D. (2014). Graph theoretical dimensions of informal organizations. In *Computational organization theory*, 107–130. Psychology Press.
- Meguerdichian, S., Koushanfar, F., Potkonjak, M., and Srivastava, M.B. (2001). Coverage problems in wireless ad-hoc sensor networks. In *Proceedings IEEE INFOCOM 2001. Conference on Computer Communications. Twentieth Annual Joint Conference of the IEEE Computer and Communications Society (Cat. No. 01CH37213)*, volume 3, 1380–1387. IEEE.
- Schlotterbeck, G., Raievsky, C., and Lefevre, L. (2018). Decentralized estimation of forest fire spread using reactive and cognitive mobile sensors. *Natural Computing*, 17(3), 537–551.
- Serugendo, G.D.M., Foukia, N., Hassas, S., Karageorgos, A., Mostéfaoui, S.K., Rana, O.F., Ulieru, M., Valckenaers, P., and Van Aart, C. (2003). Self-organisation: Paradigms and applications. In *International Workshop on Engineering Self-Organising Applications*, 1–19. Springer.
- Smith, R.G. (1980). The contract net protocol: High-level communication and control in a distributed problem solver. *IEEE Transactions on computers*, (12), 1104–1113.
- Wolfram, S. (1984). Universality and complexity in cellular automata. *Physica D: Nonlinear Phenomena*, 10(1-2), 1–35.