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Ensuring Information Availability in a Mobile MESH Network with Connectivity Restrictions

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ABSTRACT

The article investigates the problem of providing information availability for mobile MESH networks. It is shown that the main approach to ensuring information availability should be to ensure the structural connectivity of the network. It is proved that for the description of the majority of tasks of the distributed network it is expedient to use Voronoi partition and for maintenance of information availability - connectivity function. The simulation results prove the truth of the made theoretical assumptions.

Key words : Computer simulation, Connectivity function, Information availability, Mobile MESH Network, Voronoi partition.

1. INTRODUCTION

Today, the construction of various distributed systems (for example, for the protection of important objects) is based on the possibility of using certain data networks. MESH networks are increasingly used to operate systems in dynamics and in complex environments. The advantage of using the MESH architecture is the ability to transfer information between individual agents over long distances, with each agent can be both an end user and a repeater of information. At the same time, due to the dynamic nature of the network topology and the possibility of loss of communication between individual agents, the main factor of information security in this case is the availability of information.

1.1 Problem Statement

The parameters of MESH network construction significantly depend on the capabilities of data transmission media and signal propagation conditions. In mobile groups, as a rule, it is quite difficult to provide significant transmitter power and therefore the problem can be solved by increasing their number. Given the constant movement of individual agents, to ensure the connectivity of the entire network, it is necessary that each agent be visible to a number of other agents throughout the operation of the system. Thus, the main task of ensuring the availability of information in the design of distributed systems with MESH architecture is to develop a protocol that would ensure the connectivity of the structure, despite the movement of its individual elements.

1.2 Related Works Analysis

A large number of publications are devoted to the construction of MESH networks and their modeling. Thus, in [1] an in-depth analysis of data transmission protocols used for MESH networks is made. In this case, the main application of MESH networks is to provide users with access to the Internet [2]. Issues of specific application of MESH are investigated in [3], where the advantages of Mesh technology in its application to combine multiple IoT devices are analyzed. At the same time, these publications do not explore data security in MESH networks.

Security in MESH networks is analyzed in [4], but this publication does not provide security models that would be suitable for research purposes. The publication [5] on the contrary is devoted to the modeling of processes in MESH networks, at the same time, the issues of availability and connectivity of information in it are not considered.

Connectivity issues in MESH networks are discussed in the publication [6], which shows the main problems of network connectivity and approaches to its provision. The publication [7] presents a set of connectivity models. However, these models are based mainly on the probabilistic approach and do not allow to consider the system in motion. A dynamic model of maintaining connectivity is considered in [8]. However, the algorithm presented in this publication does not take into account the need for the agent to perform the task, which leads to a simple drawing of the group in one line. The concept of maintaining a network of autonomous agents was introduced in [9]. The main approach in this case was to maintain a given topology of the agent group. The problem of agent connectivity is also considered in [10], where the problem of planning the work of a group of autonomous agents in the protection of an important object is solved. In addition, in [11] a group of connected agents solves the problem of finding hidden transmitters.

Thus, existing approaches to modeling the availability of information in MESH networks based on connectivity do not allow the design of dynamic systems in which individual elements are constantly moving. The purpose of this publication is to develop an approach that would ensure the availability of information based on maintaining the connectivity of the mobile MESH network, taking into account the parameters of the deployment of a multi-agent system.

2. MOBILE MESH NETWORK MODEL WITH CONNECTIVITY RESTRICTIONS

In real life, the use of communication is often limited, and sometimes stopped altogether, the transmission of messages is sporadic, and low-power transmitters are used to keep the network hidden, allowing only short-distance communication. In this case, the transmission of messages over long distances in the MESH network is carried out by relaying them by individual nodes. Therefore, the realization of the idea of effective information exchange between all agents, when each individual agent can communicate with another with the use of repeater agents requires solving the problem of forming an effective topology of a multi-agent system. The agent transmits the information via a transmitter to a neighboring agent, which then retransmits it further. Due to the low power of the transmitters and the presence of noise (interference), the range of the agent transmitter is limited to some value r_{com}.

2.1 Mobile MESH Network Model

For further formalized description of agent communication processes based on graph theory, we construct a topology model for a multiagent MESH structure (Figure 1). In this example, the task of the group of agents is to reach the target without losing contact with the coordinating agent 1.

Let $V = \{v_1,...,v_n\}, v_i \in \mathbf{R}^d$ - the set of individual nodes of the graph. For each node V you can define a neighborhood graph $G(V)$ as an undirected graph formed by a set of vertices from V and a set of edges $E = E_G(V)$ where $E_G(V): \mathbf{R}^d \to \mathbf{R}^d \times \mathbf{R}^d$ - is a function of determining the edges, which has the property $E_G(V) \subseteq \{(v_i, v_j) \in V \times V \mid v_i \neq v_j\}$. That is, the set of edges of the neighborhood graph depends on the position of the vertices. It should also be noted that if the neighborhood graph is formed from points whose position changes over time, the neighborhood graph will also depend on time. Thus, it is possible to describe the network topology of distributed agents in the process of their movement.

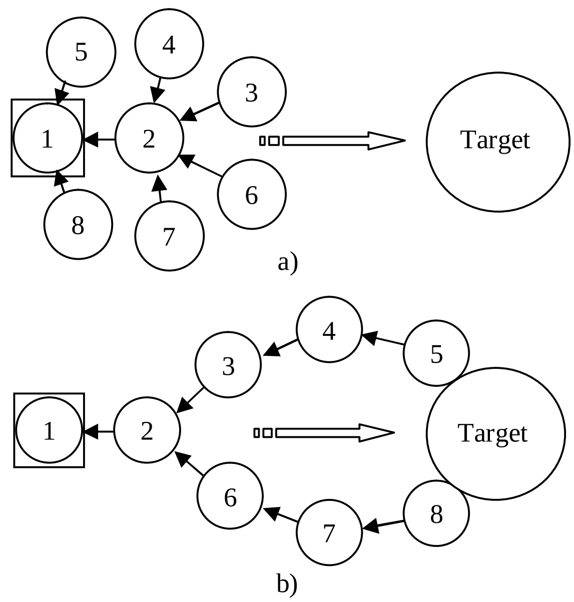

Figure 1: Dynamics of the MESH network graph moving to the target:a) the shortest connection;b) long connection.

The function of defining edges is closely related to the weight function $C_G(V) = \begin{cases} > 0, \text{ if } (v_i, v_j) \in E_G(V); \\ 0, \text{otherwise.} \end{cases}$

The use of the neighborhood graph is convenient for describing the interaction and information flows between agents in a mobile MESH network. To form a neighborhood graph, it is necessary to have a graph in which each pair of vertices is neighboring (there is a corresponding edge), and if the Euclidean distance in the pair of vertices is not greater than r_{com}:

$$E_G(V) = \{(v_i, v_j) \mid |v_i - v_j| \leq r_{com}\}. \tag{1}$$

For security or search systems, the main task of a group of agents is to deploy them effectively in order to achieve maximum coverage of a specific area while ensuring connectivity in the system. Algorithms based on the construction of Voronoi diagrams (Figure 2) proposed in [12] are most often used for this purpose.

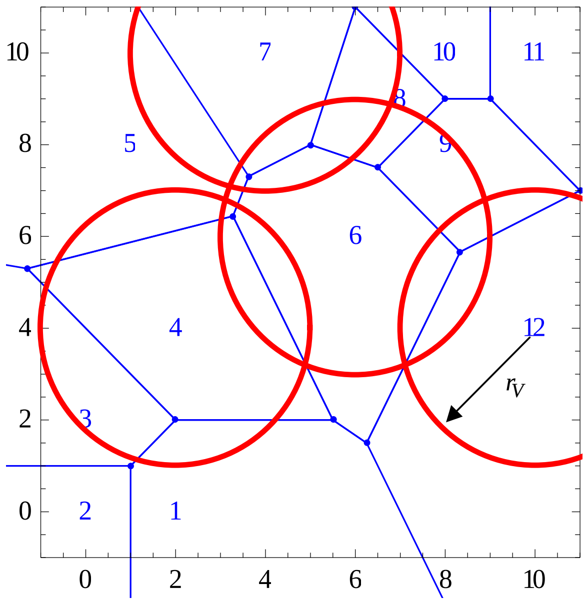

Figure 2: Voronoi diagram for 12 agents

Determining the appropriate topology of agents in Euclidean space taking into account *r*-constraints requires the implementation of the Voronoi partition [13], which for the *i*-agent is defined as

$$V_i = \left\{ x \in \Omega \,\middle|\, \left|x - z_i\right| \le min\left(\left|x - z_j\right|, r_V\right) \forall j \in J \right\}, \qquad (2)$$

where r_V – the radius that limits the Voronoi partition;J – the set of indices of individual agents.In our case, it is logical to assume that $r_V = r_{com}$.

2.2 Mobile MESH Connectivity

The operation of search agents, which is considered in the work, involves the collection of information and bringing it to the coordinating agent 1. As noted, agents can communicate through transmitters transmitting information through other agents. In order to be able to receive data from the task area in a timely manner, the network must be constantly connected. Therefore, certain connections on the network must be secure. But how to decide which network connections can be broken and which need to be maintained throughout the life of the system?

In [14], restrictions on the movement of agents are formulated, so maintaining connectivity is considered through restrictions on the distance of agents from each other, while in [15], the main limitation of building a network based on the construction of a connectivity graph. The publication [16] proposes an algorithm for calculating connected subgraphs of the connectivity graph of agents during their initialization, which is then used to build control laws in the network. Another approach to solving the problem of maintaining the connectivity of the agent network is proposed in [17], which uses a potential function to maintain connectivity.

The purpose of maintaining connectivity in this paper can be formulated more specifically than the main task of maintaining network connectivity in [18]. The interaction of agents by the radio is described using models that have already been considered in publications [19] and [20]. Since the proposed network of agents in this work requires the transfer of data to the database, this way of communication must be protected at all times. This communication path, which is the minimum frame tree that describes the minimum path from each agent to the database, is a subgraph of a graph $G_{com}(t)$ that is a communication graph of a MESH network with n agents within their communication radius.

Since this tree $\tilde{G}_{com}(t)$ is connected and $\tilde{G}_{com}(t)$ is a core tree of $G_{com}(t)$, it will be sufficient to keep this tree to maintain the connectivity of the graph $G_{com}(t)$. Therefore, the movement of agents must be limited so that all the edges of the graph $\tilde{G}_{com}(t)$ are preserved, and the agents, in this case, can perform their tasks.

2.3 Connectivity Function

All edges $(v_i, v_j) \in E_{\tilde{G}^*_{com}}$ must be protected to maintain connectivity on the graph tree $\tilde{G}_{com}(t)$. The connection between the agents is limited to a certain radius r_{com}, which means that the distance between the two agents $d = \left|z_i - z_j\right|$ must be less than r_{com}. Then, to ensure network connectivity, it is necessary to formulate some potential function, which will depend on the distance $d$between agents and some threshold value R.

A function $f\!:\!D \to \mathbf{R}_0^+$, where $D = \{ d \mid 0 \le d < R \}$, can be considered as a **connectivity function** if it satisfies the following conditions: 1) $f(0) = 0$; 2) $f(d)$ is continuous, differentiable and strictly monotonically increasing in the interval $d \in D$; 3) $\lim\limits_{d \to R} f(d) = +\infty$.A function that satisfies certain properties of the connectivity function can be represented as

$$f(d) = d \big/ (R - d)^m, \qquad (3)$$

where $m$can be entered by the developer. Figure 3 shows the graph of (3) for R = 5 and m = 8.The use of (3) guarantees connectivity in the MESH network, which can be proved as follows. Let $V = f(d)$ – be a connectivity feature for $d < R$.

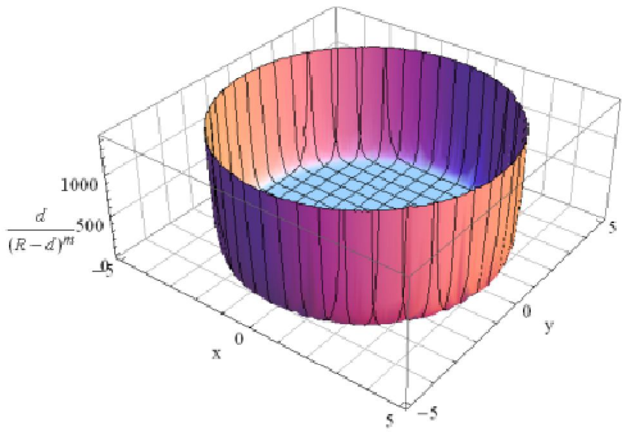

Figure 3: Example of the connectivity function graph

If there is something like δ that $0 \le \delta < R$ and $\dot{V} \le 0$, $\forall d \mid \delta \le d < R$ then $d < R$ $\forall t$ the agent's connection to the nearest neighbor is guaranteed. Since from $\dot{V} \le 0$ for $0 \le d < R$, given $V = f(d)$ that $\frac{\partial f}{\partial d} \le 0$, then, according to the connectivity function, a decrease $\frac{\partial f}{\partial d}$ causes a decrease $\delta \le d < R$ and therefore $d < R$, $\forall t$.

2.4 Connectivity through Repeaters

The purpose of the connectivity function is to maintain communication while the agent is performing its functions. The dynamics of the movement of the i-th agent can be described by the following equation:

$$\dot{z}_i = u_i^{connect} + u_i^{control} , \qquad (4)$$

where $u_i^{connect}$ – connectivity function;

$u_i^{control}$ – movement control component of the agent in accordance with the defined task.

In order to maintain the connectivity of the tree $\tilde{G}^*_{com}$, it is necessary to ensure the existence of all edges $E_{\tilde{G}^*_{com}}$. Since the arcs in the core tree are determined by the nearest neighbor-repeater of each agent, it can be said that it is necessary to maintain communication between the i-agentand its neighbor-repeater h_i. This means that the distance to the repeater neighbor must be less than the communication radius. In order to achieve this, it is necessary to formulate a function to ensure connectivity with distances from each i-agent to its neighbor-repeater h_i

$$f_i = f(d_i) = f|_{d_i} , \quad d_i = \left| z_{h_i} - z_i \right| . \qquad (5)$$

To keep agents connected to their repeaters, the distance $d_i$must be kept to a minimum. Since the increase in the distance d_i is directly related to the increase in the value of the function $f(d_i)$, the agents must move in the direction of the negative values of the gradient of the function f_i

$$\dot{z}_i = -\left(\frac{\partial f_i}{\partial z_i} \right)^{\mathrm{T}} + u_i^{control} . \qquad (6)$$

The connectivity function f_i and the agent movement function $\dot{z}_i = -\frac{\partial f_i}{\partial z_i} + u_i^{control}$ with $\left| u_i^{control} \right| < \infty$ ensure that the agent is connected to the repeater. This can be proved by considering the derivative of the function $V_i = f_i$ by time

$$\dot{V}_i = -\frac{\partial f_i}{\partial z_i} \cdot \dot{z}_i = \frac{df_i}{dd_i} \frac{\partial d_i}{\partial z_i} \cdot \dot{z}_i . \qquad (7)$$

The distance d_i is the distance between the i-agent and its repeater h_i and is determined $d_i = \left| z_{h_i} - z_i \right|$ where the expression in parentheses is the Euclidean distance, which in our two-dimensional space can be defined as $d_i = \sqrt{\left(z_{h_i,x} - z_{i,x} \right)^2 + \left(z_{h_i,y} - z_{i,y} \right)^2}$. Then the derivative from $d_i$byz_i can be calculated as

$$\frac{\partial d_i}{\partial z_i} = \frac{1}{2} \frac{1}{\sqrt{\left(z_{h_i,x} - z_{i,x} \right)^2 + \left(z_{h_i,y} - z_{i,y} \right)^2}} \times$$
$$\times \left[-2\left(z_{h_i,x} - z_{i,x} \right) - 2\left(z_{h_i,y} - z_{i,y} \right) \right] = -\frac{\left(z_{h_i} - z_i \right)^{\mathrm{T}}}{d_i} . \qquad (8)$$

Based on the previous calculations and the dynamics of the agents'movement (4), formula (7) can be rewritten

$$\dot{V}_i = \frac{df_i}{dd_i} \left(-\frac{df_i}{dd_i} \frac{\left(z_{h_i} - z_i \right)^{\mathrm{T}} \left(z_{h_i} - z_i \right)}{d_i^2} + \frac{\left(z_{h_i} - z_i \right)^{\mathrm{T}}}{d_i} u_i^{control} \right) . \qquad (9)$$

Since $a^{\mathrm{T}} b = |a||b| cos(a,b)$, the formula (9) can be written as

$$\frac{\left(z_{h_i} - z_i \right)^{\mathrm{T}}}{d_i} \frac{\left(z_{h_i} - z_i \right)}{d_i} =$$
$$= \frac{1}{d_i^2} \left| z_{h_i} - z_i \right|^2 cos\left(z_{h_i} - z_i , z_{h_i} - z_i \right) . \qquad (10)$$

Given that $\left|z_{h_i} - z_i\right| = d_i$ and $cos\left(z_{h_i} - z_i, z_{h_i} - z_i\right) = 1$, then $\dfrac{\left(z_{h_i} - z_i\right)^{\mathrm{T}}}{d_i} \dfrac{\left(z_{h_i} - z_i\right)}{d_i} = 1$.

The second part in parentheses (9)

$$\frac{\left(z_{h_i} - z_i\right)}{d_i} u_i^{control} =$$

$$= \frac{1}{d_i}\left|z_{h_i} - z_i\right|\left|u_i^{control}\right| cos\left(z_{h_i} - z_i, u_i^{control}\right) = \quad (11)$$

$$= \left|u_i^{control}\right| cos\left(s_{h_i} - s_i, u_i^{control}\right) \le \left|u_i^{control}\right|.$$

From (10) and (11) equation (9) can be estimated as

$$\dot{V}_i \le \frac{df_i}{dd_i}\left(-\frac{df_i}{dd_i} + \left|u_i^{control}\right|\right). \quad (12)$$

Under the conditions imposed, when $\dot{V} \le 0$ it is important to provide $\dfrac{df_i}{dd_i}\left(-\dfrac{df_i}{dd_i} + \left|u_i^{control}\right|\right) \le 0$ that is $-\dfrac{df_i}{dd_i} + \left|u_i^{control}\right| \le 0$, where

$$\frac{df_i}{dd_i} \ge \left|u_i^{ynp}\right|. \quad (13)$$

Based on the previous considerations, we assume that there is an inverse function $\left(\dfrac{df}{dd}\right)^{-1} : \mathbf{R}_0^+ \to D$. The absolute value of the control function $\left|u_i^{control}\right| : \mathbf{R}^2 \to \mathbf{R}_0^+$ determines the mapping of a two-dimensional Euclidean space to a set of positive real numbers. Since $\mathbf{R}_0^+$ there is an area for defining an inverse function $\left(\dfrac{df}{dd}\right)^{-1}$, there is also an inverse control function $\left(\dfrac{df}{dd}\right)^{-1}\Bigg|_{\left|u_i^{control}\right|}$.

In order to determine the upper bound δ_i that would satisfy $\dot{V} \le 0$ for $d > \delta_i$, both parts of inequality (13) must be equal. Then δ_i can then be defined through the inverse function as

$$\left(\frac{df}{dd}\right)^{-1}\Bigg|_{d=\delta_i} = \left|u_i^{control}\right|, \delta_i = \left(\frac{df_i}{dd_i}\right)^{-1}\Bigg|_{\left|u_i^{control}\right|}. \quad (14)$$

Since the inverse function is also defined in *D*, so $0 \le \delta_i < R$ is guaranteed. Therefore, for $d_i \ge \delta_i \to \dfrac{df}{dd} \ge \dfrac{\partial f_i}{\partial \delta_i}$ the agent's connectivity with the repeater agent also follows.

The simulation of the movement of 8 agents with the function of maintaining connectivity (3) for the initial parameters $m = 10$ and $r = 3$ is shown in Figure 4.

Figure 4 shows that at the initial moment *t* = 0 all agents are placed concentrated as close as possible to the base (agent 1). Then, under the influence of the gradient field of the target, they begin to move towards the target. In order to carry out surveillance or security tasks, agents try to disperse as widely as possible. This is facilitated by the mathematical model of Voronoi partition, which tries to cover a given territory evenly. At the same time, in order to reach the target agents are forced to be drawn into the line without losing contact with each other and with the base through repeaters. In this way, the agent connection graph degenerates to the minimum core tree, and the agents themselves move in semicircular trajectories.

The ability to transfer information on such a network is provided by a connectivity function. As a result of such application, the system provides connectivity, which is the basis of information availability.

3. CONCLUSION

1. Information availability in a mobile MESH network should be provided by protocols that would maintain the connectivity of its structure. To do this, the structure must identify the key elements that collect the main flows of information, and define the boundaries and direction of movement of individual agents.

2. Maintaining connectivity in a mobile MESH network is based on a connectivity function that allows agents to create different topologies while remaining within range of communications. This ensures the continuity of the information space for the duration of tasks with the relative "freedom of movement" of individual agents. The Voronoi partition model is the most suitable for monitoring or protection tasks. Such collective interaction of the distributed system due to self-organization algorithms brings the behavior of individual entities (agents) closer to the behavior of a group of animals, which ensures their survival, because, as we know, the most viable groups are groups that use a flock management strategy.

3. As a direction of further research may be a wide range of issues of interaction of agents in the system, protocols for the transfer of information between agents and models of movement of individual elements.

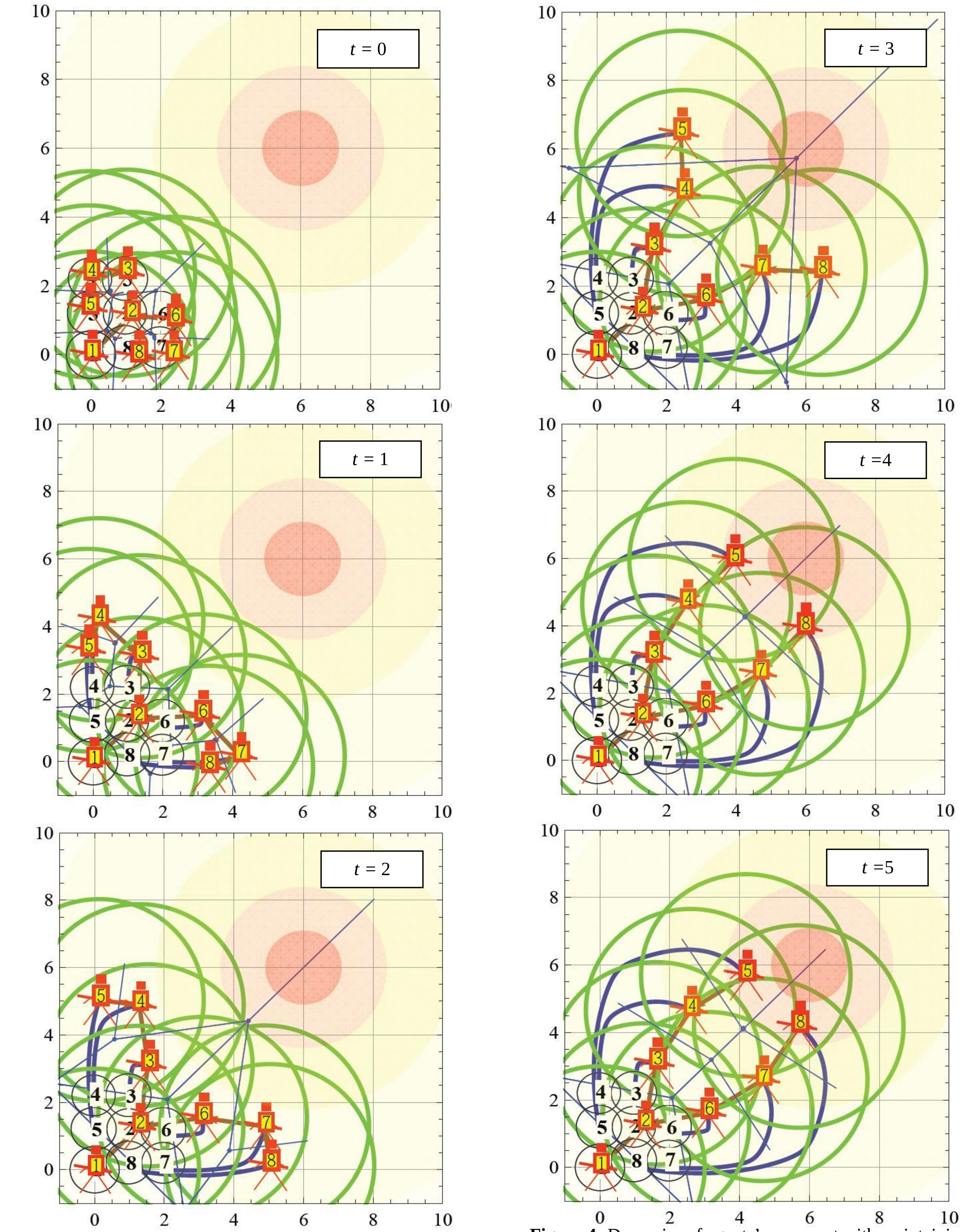

Figure 4: Dynamics of agents' movement with maintaining connectivity

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