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Characteristics of Autonomously Configured Structure Formation Based on Power Consumption and Data Transfer Efficiency

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***Abstract*—In MANETs (mobile ad hoc networks), mobile terminals can connect with each other directly and constitute communication networks without network infrastructure such as base stations and access points of wireless LANs that are connected to wired backbone networks. Therefore, MANETs are expected to be tolerant networks in an emergency situation (e.g., large earthquake) in which most infrastructure is destroyed. We have proposed an autonomous decentralized structure formation technology based on local interaction as the terminals' action method and, moreover, have applied the proposed structure formation technology to the autonomous decentralized clustering method of MANETs. In addition, we have evaluated the characteristics of this technology from the point of view of the power consumption during "cluster configuration." However, this technology has previously not been evaluated in terms of the characteristics of the power consumption and data transfer efficiency at the time of packet routing. In this paper, we compare the proposed clustering model with a bio-inspired model that is based on the reaction-diffusion equation in the routing of the data.**

***Keywords*-autonomous decentralized control; local-action theory; mobile ad hoc network; clustering;**

I. INTRODUCTION

Large-scale disasters such as tsunami and earthquakes cause serious damage to any network infrastructure as well as to buildings and people. After these disasters, it is necessary to collect information on the status of the disaster quickly and to issue evacuation orders based on the gathered information promptly. In order to solve these subjects, the defects in network functionality need to be recovered as quickly as possible. Because such a situation is wildly confused immediately after the disaster (a chaotic situation where network structures and network infrastructure have been destroyed), the network protocols designed under the assumptions of a normal environment may not satisfy the operating requirements in such an emergency, and prompt network recovery may not be possible. This problem can be solved by creating an environment in which the remaining devices can operate effectively. One solution is a MANET (mobile ad hoc network) [1], [2]; mobile terminals can connect to each other directly and constitute communication networks without network infrastructure such as base stations and access points of wireless LANs that are connected to the wired backbone networks.

Clustering mechanisms for MANETs have been proposed for power saving and load balancing [3], [4]. They are an important technology because they make it possible to reduce the power consumption of each node and extend the life of the network after the disaster. These mechanisms use metrics such as each node's battery reserves [5] and performance (e.g., processing speed, memory, and other parameters) [6]. In these works, the global information for the network state is needed to obtain a globally optimal solution for the cluster structure, but practically, it is difficult to gain global information because information exchange is structurally limited in MANETs. This emphasizes the importance of autonomous cluster configuration methods wherein globally optimum structures can be developed from only local information to execute traffic control, path control, and network resource management. In particular, an ability to produce a well-ordered network configuration even in the chaotic situation of an emergency is required. This paper focuses on a clustering mechanism to provide self-configuring mechanisms.

We have already proposed a framework for a novel autonomous decentralized mechanism based on local interaction [7]. This framework is based on the interplay between local interaction and the solution provided by a partial differential equation. As a specific example, we proposed an autonomous decentralized formation of structures with a finite spatial size and showed the proposal's applicability to autonomous clustering in MANETs [8]. Our clustering method allows the nodes to act flexibly in a manner based only on the information each individual node is aware of, i.e. its individual situation, and it can yield the structure of clustering which reflects the characteristics of the given environmental conditions (e.g. the distribution of the residual battery power of terminals, the position of power supplies,

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or the node degree of mobile terminals). Other works on clustering based on local information include the well-known bio-inspired approach, which uses a Turing pattern of reaction-diffusion equations [9], [10]. Our autonomous decentralized structure formation technique in [8] (proposed model) can configure clusters faster from the point of the time constant, by a factor of 10 or more, than an existing method [9] (bio-inspired model) [11]. This means that the network configuration can be recovered quickly by our proposed clustering method. In addition, the clusters yielded by the proposed model have approximately double the lifetimes of those yielded by the bio-inspired method in terms of power consumption in the control packet transfer phase [12]; however, [12] has taken no account of the packet transfer phase of communication.

This study first creates clusters by the autonomous decentralized methods of [8] and [9] on a MANET modeled as a unit disk graph. The Hi-TORA algorithm [13], which is a kind of hierarchical routing (cluster-based routing), is assumed to be running on the network. Then, we elucidate the network lifetimes when sending data packets in clusters formed by the proposed model and the bio-inspired model using the metrics of FND (first node die) time (FND time is the time until the first failure of a node due to battery exhaustion) and the probability of live nodes. Note that live nodes denote nodes who still have remaining battery power. Next, we evaluate the information-gathering capabilities (amount of data that the sink node has received) of the clusters yielded by these methods.

This paper consists of the following sections: In Sec. II, we present the framework of our proposed autonomous decentralized structure formation technology. In Sec. III, we describe Hi-TORA, which is the hierarchical routing technique used in this study. We evaluate the characteristics of the proposed method in Sec. IV, and Sec. V provides the concluding remarks.

II. Clustering method based on autonomous decentralized structure formation

This section provides an overview of the autonomous decentralized structure formation proposal that uses back diffusion drift. It also describes the bio-inspired models with which the proposal is compared.

A. *Overview of back-diffusion-based autonomous decentralized structure formation technology*

In this section, we will explain autonomous decentralized control in n-dimensional space. Let the density function (density distribution) of a certain *quantity* at time t and position $\boldsymbol{x}$ be $q(\boldsymbol{x},t)$. The initial value of $q(\boldsymbol{x},0)$ can be considered as the metric, for example, the residual battery life of each node. Local behavior corresponds to changing the value of $q(\boldsymbol{x},t)$ at each point. In an autonomous decentralized structure formation, flow $\boldsymbol{J}(\boldsymbol{x},t)$ (the operation rule that changes the value of $q(\boldsymbol{x},t)$) is expressed as

$$\boldsymbol{J}(\boldsymbol{x},t) = -c\,\boldsymbol{f}(\boldsymbol{x},t)\,q(\boldsymbol{x},t) - c\,\sigma^2\,\boldsymbol{\nabla}\,q(\boldsymbol{x},t) \qquad (1)$$

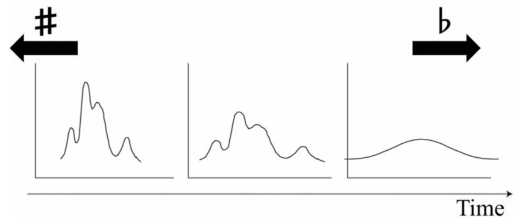

Figure 1. Diffusion and back diffusion

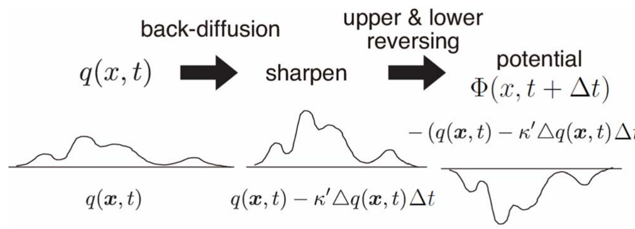

Figure 2. Determining potential $\Phi(x,t)$ according to back diffusion

where the first and the second terms denote the drift and diffusion terms, respectively. The temporal evolution of distribution $q(\boldsymbol{x},t)$ that corresponds to this change is given by

$$\frac{\partial}{\partial t}\,q(\boldsymbol{x},t) = c\,\boldsymbol{\nabla}\cdot(\boldsymbol{f}(\boldsymbol{x},t)\,q(\boldsymbol{x},t)) + c\,\sigma^2\triangle q(\boldsymbol{x},t), \qquad (2)$$

where $\triangle = \boldsymbol{\nabla}^2$. c (>0) denotes the rate of the temporal evolution of $q(\boldsymbol{x},t)$, and σ^2 denotes the variance of the normal distribution that is converged upon. $\boldsymbol{J}(\boldsymbol{x},t)$ represents the amount of spatial movement of $q(\boldsymbol{x},t)$; note that the total value of $q(\boldsymbol{x},t)$ does not change over time. Equation (2) is a second-order differential equation. Therefore, this operation rule can be realized by interaction among adjacent nodes and can be extended to arbitrary network topologies. The introduction of $\boldsymbol{f}(\boldsymbol{x},t)$ eliminates the need to set a coordinate system in the network.

As a more intuitive explanation, we consider a potential function $\Phi(\boldsymbol{x},t)$ instead of function $\boldsymbol{f}(\boldsymbol{x},t)$:

$$\boldsymbol{f}(\boldsymbol{x},t) = -\boldsymbol{\nabla}\,\Phi(\boldsymbol{x},t). \qquad (3)$$

Choosing $\Phi(\boldsymbol{x},t)$ appropriately yields autonomous decentralized control that does not depend on a coordinate system. We consider how to determine the drift term from the distribution, $q(\boldsymbol{x},t)$, which is local information. Because the potential function $\Phi(\boldsymbol{x},t)$ should result in maintaining the distribution within a certain finite spatial extent, contrary to the effect of diffusion, $\Phi(\boldsymbol{x},t)$ is, after discrete time Δt, given by

$$\Phi(\boldsymbol{x},t+\Delta t) = -\left(q(\boldsymbol{x},t) - \kappa'\triangle q(\boldsymbol{x},t)\,\Delta t\right), \qquad (4)$$

where $\kappa' > 0$ and $\Phi(\boldsymbol{x},t)$ are periodically renewed at intervals of Δt. The meaning of this equation can be expressed as follows:

- We let the time progression of the diffusion phenomenon with diffusion coefficient κ' be reversed (back diffusion).
- Next, we reverse the distribution (up and down) and regard the completed distribution as the potential.

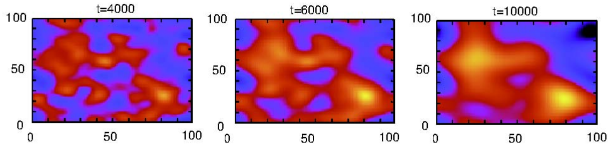

Figure 3. Cluster structure formation by our proposed scheme (after $4,000,\ 6,000,\ 10,000$)

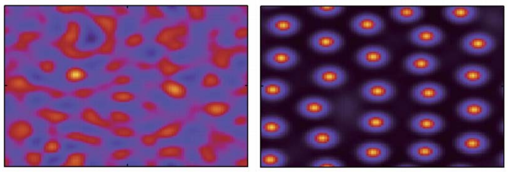

Figure 4. Turing patterns for bio-inspired model

The temporal evolution of the distribution becomes a flat state in the forward direction of time for general diffusion (Fig. 1). For Eq. (4), the method of generating potential $\Phi(\boldsymbol{x}, t+\Delta t)$ by using distribution $q(\boldsymbol{x}, t)$ is shown in Fig. 2. Because of the effect of the drift term, including the potential, the peak of distribution $q(\boldsymbol{x}, t)$ is emphasized, and the distribution shape is sharpened. The effect of the diffusion term, on the other hand, is to flatten the distribution. A structure with a finite spatial size can be formed by balancing one effect against the other (Fig. 3). The peak of distribution is the representative node of the cluster, and the extent of the distribution is the cluster.

B. Bio-inspired model based on reaction-diffusion equations

The bio-inspired model [9] is an autonomous decentralized structure formation approach that uses Turing patterns. Invented by Alan Mathison Turing, a Turing pattern is a mathematical model used to describe the pattern formation process on the body surfaces of animals. A Turing pattern is formed with reaction-diffusion equations (Eq. (5) and (6)). Each node in the network holds two factors, activator a and inhibitor h, and these values change over time according to the following differential equations:

$$\frac{\partial a}{\partial t} = \frac{ca^2}{h} - \mu a + \rho_0 + D_a \nabla^2 a, \tag{5}$$

$$\frac{\partial h}{\partial t} = ca^2 - \nu h + \rho_1 + D_h \nabla^2 h, \tag{6}$$

where c, ρ_0, and ρ_1 are parameters that increase effects of the activator and inhibiter, and μ and ν are parameters that decrease the effects of the activator and inhibitor, respectively. Moreover, D_a and D_h are parameters describing the rate of diffusion for the activator and inhibitor, respectively. From Eqs. (5) and (6), it is found that the spatial pattern appears gradually over time (Fig. 4), and then the peak of the created pattern denotes the representative node of the cluster and the extent of the pattern denotes that of the cluster. [14] offers research on the parameter design for systems based on reaction-diffusion equations. It is, in general, significantly more difficult to design parameters for the bio-inspired model than the proposed model because the former has so many more parameters.

III. Hierarchical routing Hi-TORA

In this section, we describe the Hi-TORA algorithm [13], which is the hierarchical routing scheme applied to MANETs in this paper.

A. Overview of Hi-TORA

Hi-TORA is a kind of hierarchical routing (cluster-based routing) scheme used in MANETs. Hi-TORA has two phases according to the domain in which the routing algorithm operates: the intra-cluster (within a cluster) and the inter-cluster (among clusters) phases. The traditional link-state-type routes (shortest path routes) are provided for intra-cluster routing. For inter-cluster routing, on the other hand, Hi-TORA applies a TORA (temporally ordered routing algorithm) [15] to the routing among clusters and regards one cluster as one virtual node in this case. In this way, Hi-TORA calculates the routing path from the source node to the sink node based on two phases when the sink node belongs to a different cluster from the source node. We briefly explain the routing algorithm for each phase below.

B. Routing for the intra-cluster phase

For the intra-cluster phase, Hi-TORA performs the link-state routing algorithm, which finds the shortest path between the source node and the sink node using Dijkstra's algorithm. The shortest path is the one with a minimum number of hops. When the source node and the sink node lie in the same cluster, the source node sends the data to the sink node via the shortest path. Otherwise, the source node sends the data to the boundary node that adjoins the next cluster on the path to the sink node. If more than one boundary node exists, the source node chooses the node that has the lowest node ID. If two or more boundary nodes exist, the source node chooses the node that has the lowest node ID as the boundary node.

C. Routing for the inter-cluster phase

Hi-TORA adopts TORA to execute on-demand path calculations for the routing algorithm among clusters because TORA has high adaptability to a node's mobility in the network. TORA establishes the DAG (directed acyclic graph) in which the sink node is regarded as a root. Then, TORA determines the logical direction of the links to the sink node by using the DAG, where the calculation of the direction of each link uses the metric called "$height$." TORA controls the entire network so as to maintain multiple paths between the source and sink nodes. Thus, the overhead of the control packets for TORA inevitably increases according to the number of nodes. Here, the overhead can be reduced by assuming one cluster to be one virtual node, and so the $height$ can be set not to each link but to each cluster. When a source node wants to communicate with a sink node, the source node sends an RTS (request to send) packet toward the sink node. Then, the $height$ is set for all clusters that received the packet. The destination cluster's $height$ is set to 0. The closer the cluster is to the source node, the larger $height$ is set for the cluster. Thus, the $height$ of the source

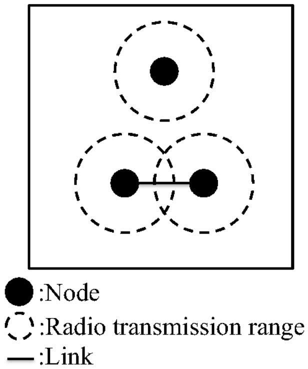

Figure 5. Unit disk graph network

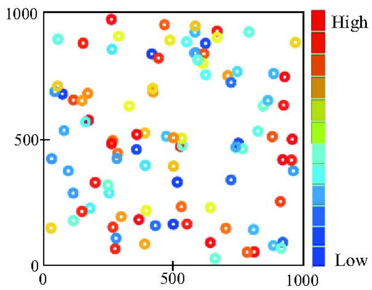

Figure 6. Initial battery distribution

cluster to which the source node belongs is the highest value in the network, and the $height$ of the destination cluster to which the destination node belongs is the lowest value. The data packets that are generated by the source node are forwarded via the clusters with lower $height$.

Note that the clusters on which Hi-TORA in [13] operates are configured by the clustering method in [16]. In evaluations of this paper, we use the proposed model and the compared bio-inspired model for the clustering method.

IV. Evaluation

In this section, we show the results of the comparative evaluation for the temporal evolution of live nodes, the FND time, and data transfer efficiency. We assume the following two situations for each experiment:

1) Each node is fixed in the network (fixed nodes).
2) Each node moves in the network (mobile nodes).

A. Evaluation for fixed nodes

The network is a unit disk graph (UDG) of $1,000$ m $\times$ $1,000$ m, see (Fig. 5). The UDG is a kind of intersection graph of equal-radius circles. In Fig. 5, each node has a fixed radio transmission range with an equal radius. We assume that two nodes are connected by a link and can communicate with each other when their ranges overlap each other.

Table I shows the specifications of the experimental environment. We refer to [17] for the battery consumption of each node. We assume that a node becomes unavailable (dead) if its battery capacity falls to 0. Figure 6 shows the initial battery distribution for each node. The network model has a torus topology to exclude the influence of the boundary. In Figure 6, high and low values are expressed as cool and warm colors, respectively. The initial value, $q(\boldsymbol{x}, 0)$, for our proposed model (or $a(\boldsymbol{x}, 0)$, $h(\boldsymbol{x}, 0)$ for the bio-inspired model) is the same as the value of the initial battery capacity. The initial battery capacity for each node is a uniform random number [5, 15]. Thus, the average of the initial battery capacity is 10 J, which refers to [6]. The cluster formation is performed from $t = 0$ by each model, and the execution of the routing algorithm by Hi-TORA and the transmission of data packets start from $t = 1.001$.

Next, we explain the routing procedures. First, each node generates data packets (1 pkt = 1.5 kB) with time intervals that follow the exponential distribution with $\lambda = 0.004$. The value of λ is set according to [18]. The source node sends the data packets to the sink node through the multi-hop path that Hi-TORA computes. Once established, the routing path is maintained until the transmission of packets is completed. For simplification, the sink node can receive multiple packets simultaneously, that is, packet collisions are not considered. If the path to the sink node cannot be found, the source cancels the transmission of packets. Only the sink node has a main power supply, so its battery power is never exhausted. The parameters of the proposed model and the bio-inspired model are shown in Tables II and III, respectively. The parameters of the bio-inspired model were taken from [9] and those of the proposed model are adjusted so that it yields the same number of clusters as the bio-inspired model. For the cluster formation, adjacent nodes exchange one control packet per second (1 pkt = 8 bytes, and note that it is the control packet used for cluster formation). Routing-control packets by Hi-TORA (1 pkt = 8 bytes) are used in inter-cluster communication to set the $height$ for each cluster on the path.

Figure 7 shows the temporal evolution of the probability of live nodes for both models. Experimental results are the averages of 30 trials. The horizontal axis shows the time, and the vertical axis shows the live node probability. We can see from these results that the proposed model offers a longer survival time than the bio-inspired model. One of the reasons is that the latter needs more control packets for cluster configuration. The other is that our proposed model forms clusters according to the distribution of the initial battery power. On the other hand, the clusters that are formed by the bio-inspired model are arranged at equal intervals regardless of the distribution of the initial battery power, and the number of nodes that belong to each cluster becomes approximately uniform. For the bio-inspired model, therefore, the above reasons cause an increase in clusters according to which data packets are transmitted, and as a result, power consumption increases. Table IV shows the FND times for the proposed model and the bio-inspired model. It shows that the proposed model has longer FND times, by 587 s, than the bio-inspired model. The reason for these results is mentioned above. In Table V, we show the amount of data received by the sink node for the proposed model and the bio-inspired model. In this result, clusters

Table I
EXPERIMENTAL ENVIRONMENT (FIXED NODES)

Network	Unit Disk Graph (UDG) of $1,000$ m $\times$ $1,000$ m
Number of nodes	101 (One of which is sink node)
Transmission range of node	250 m
Initial battery reserve of node	uniform random numbers in the range $[5, 15]$ $\times 1$ J
Battery consumption	1 μ J/bit (transmission) 0.1 μ J/s (processing of representative node)
Position of sink node	(500 m, 500 m)
Simulation time	$20,000$ sec
Number of Simulations	30

Table II
PARAMETERS OF PROPOSED MODEL

c	σ^2	κ'
0.05	0.5	0.15

Table III
PARAMETERS OF BIO-INSPIRED MODEL

c	0.001
μ	0.05
ν	0.1
ρ_0	0.04
ρ_1	0.02
D_a	0.00122273
D_h	0.00180619

formed by our model can gather more data than by a bio-inspired model, and the difference in the amount of received data is $1,092$ packets. The reason is that many nodes die early, and the route to the sink node disappears because the cluster configuration by a bio-inspired model consumes more battery power as compared with our proposed model.

B. Evaluation for mobile nodes

Next, we experimented using mobile nodes in MANETs. Each node moves by the random direction model every second, and each node's average speed is 1.3 m/s. Note that the sink node is fixed. We assume that the user is moving with the terminal, and battery consumption does not occur owing to the movement of the node. Other conditions are the same as in Table I. Figure 8 shows the temporal evolution of the probability of live nodes for both models. The horizontal axis is the time, and the vertical axis is the probability of a node being live. We can see from this result that the proposed model offers a longer survival time than the bio-inspired model. Table VI shows the FND times for the proposed model and the bio-inspired model. From this result, clusters configured by our model have a longer FND time, by 534 s, than those configured by the bio-inspired model. The difference in the shape of the configured cluster and the number of control packets used influences these results for the same reasons as described in Sec. IV-A. Table VII shows the amount of data received by the sink node for our proposed model and the bio-inspired model. This result shows that clusters configured by our model can gather more

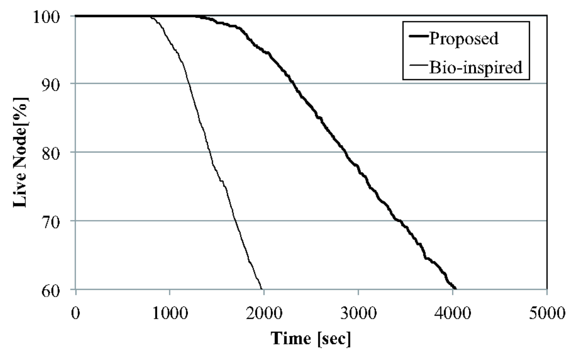

Figure 7. Temporal evolution of probability of live nodes (fixed node)

Table IV
FND TIME (FIXED NODE)

proposed	bio-inspired
$1,624$ s	$1,037$ s

Table V
AMOUNT OF TOTAL RECEIVED DATA (FIXED NODE)

proposed	bio-inspired
$1,894$ pkt	802 pkt

information, by $1,168$ packets, than those configured by the bio-inspired model. In addition, the amount of data that can be received by the sink node becomes larger in both models, compared with the results of Table V. The reason is because, on one hand, many paths have disappeared owing to the death of many nodes, and on the other hand, new paths are generated by node movement.

We can see from these results that our proposed model can restrain the power consumption and a great deal of data can be transmitted compared with the bio-inspired model.

V. CONCLUSION

We have proposed an autonomous structure formation scheme based on local knowledge and have applied it as a clustering method for MANETs. In this study, we compared the proposed clustering model with a bio-inspired model that is based on the reaction-diffusion equation. As the routing protocol, we use the Hi-TORA algorithm, which is one kind of cluster-based routing for ad hoc networks. Our evaluation focused on the temporal evolution of the live node rate, the FND time, and the data transfer efficiency. The clusters

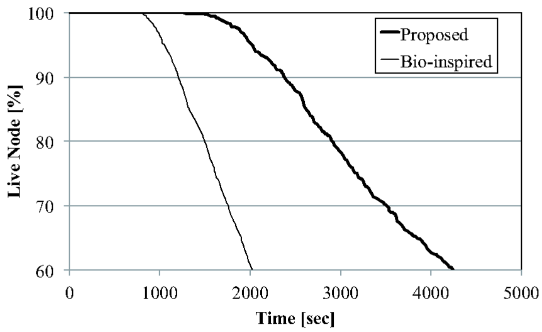

Figure 8. Temporal evolution of probability of live nodes (mobile node)

Table VI
FND TIME (MOBILE NODE)

proposed	bio-inspired
$1,565$ s	$1,031$ s

Table VII
AMOUNT OF TOTAL RECEIVED DATA (MOBILE NODE)

proposed	bio-inspired
$1,978$ pkt	810 pkt

yielded by the proposed model are superior in all respects to those of the bio-inspired model. The proposed model can yield clusters that can operate for longer periods of time and so maintain communication even after natural disasters. In addition, more data can also be transferred.

Future work includes investigating compatibilities with routing algorithms except for Hi-TORA and extending our clustering algorithm with high flexibility.

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