Wireless Sensor Networks Based on Bio-Inspired Algorithms

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Abstract. The goal of bio-inspired is to resolve human problems by studying and mimicking the characteristics of organisms or design elements which can be found in nature. Wireless sensor networks are used in a variety of fields but have limited network lifespans, so various research is being performed on the subject. In particular, research is being performed on observing and modeling the behavioral principles of various organisms to use in bio-inspired algorithms for efficient routing techniques in large-scale networks. In this research, we studied the pheromones used in ant communication and designed the techniques for energy efficiency improvement and traffic distribution by applying them to the proposed network. We designed biomimicry technology called the Wireless Sensor Networks Based on Bio-inspired Algorithms, and by analyzing and applying the similarities between communication systems and biological systems, our system was able to show improved performance in terms of extended network lifespan, optimized path selection, etc. In simulation results, the proposed routing algorithm has a short information collection time and low energy consumption, and through this it is able to maximize network energy efficiency.

Keywords: Bio-inspired algorithm · ACO algorithm · WSN · Pheromone

1 Introduction

The small sensors that constitute wireless sensor networks have functions for detecting a variety of forms of information, such as light, sound, temperature, and pressure, processing the detected information as needed for a certain purpose, and transmitting it to a base node [1]. Due to the capabilities of these sensors, wireless sensor networks are used in a variety of scenarios in such fields as environmental surveillance, disaster prevention, and healthcare [2]. However, despite these features, cases often arise where the sensors cannot be recharged. Thus, path techniques for maximizing network lifespan have emerged an important area of research. The research has focused on

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efficient routing techniques for large-scale networks that apply biomimicry algorithms modeled on the behavioral principles of various organisms.

Unlike top-down centralized control methods, which control the behaviors of entities en masse, biomimicry algorithms are bottom-up distributed processing algorithms in which each entity independently performs simple movement to create a consistent overall form [3].

Pheromones are excretions used to communicate by animals of the same species. Pheromones are a substance similar to hormones, and act to strongly attract other entities of the same species. Ants can be seen as the typical example. Pheromones are also excreted by bees and other insects. It is clear that they play a significant role in communication and recognition among animals [4].

When ants find the shortest path to a destination, they exchange information in an indirect manner through pheromones. If an ant leaves a trail of pheromones along a path it has taken, when other ants travel along the path, they choose their route according to the strength or weakness of the pheromone that was left. If it is a path that has been traveled by several ants, the pheromones are strong, and the likelihood that the path is an optimal one is high. Once the path is determined, the ants all move along the optimal path along which the pheromones are concentrated.

If humans use these functions to create an algorithm based on natural principles and structures in organisms instead of mere trial and error, they can find answers to problems similar to ones faced by these organisms.

Biomimicry algorithms mainly have been applied to optimization algorithms, and of those, the ant colony optimization algorithm, which is modeled on the process of ants finding optimal paths based on the excreted pheromones, offers an efficient routing method for complex tasks using the average values of nearby information of entities in a large-scale network [5].

In this paper, we propose a technique for selecting optimal paths and improving energy efficiency in a wireless sensor network using the ant colony optimization algorithm, which is a biomimicry algorithm [6–8]. The basic design requirements of the proposed network are as follows:

a. Sensors have a limited amount of energy. Thus, the routing algorithm must be designed to find energy-efficient paths to extend the network's lifespan.
b. Aside from energy efficiency, the routing algorithm for the wireless sensor network must be designed so that it can operate many sensors for a long time by distributing data throughout the network.

In this paper, we qualitatively analyze the similarities between communications systems and biological systems to show that biomimicry algorithms can serve as a solution for the major problems in communication networks, i.e., path selection and energy efficiency. We design a set of algorithms called WiBiA (Wireless Sensor Networks Based on Bio-inspired Algorithms) using the ant colony optimization algorithm, which is the main biomimicry algorithm used in communication networks.

The remainder of this paper is organized as follows: Sect. 2 first describes the proposed network model to finding the optimal solution to the problem, and we analyze it using the experimental results. Section 3 contains the conclusions of this study and directions for future research.

2 Wireless Sensor Networks Based on Bio-Inspired Algorithms

The ACO algorithm is well known as a method suitable for selecting the optimal path in packet routing but it has the drawback of stagnation. It also leads to problems whereby it lowers the probability of selecting other paths, which causes congestion along the optimal path. The issue is that if congestion occurs along the optimal path, the path is no longer optimal, and the overall energy consumption of the network increases. In this paper, we propose the algorithm below with the intention of designing an efficient wireless sensor network and overcoming problems that occur when using biomimicry algorithms.

2.1 CFA: Congestion-Free Algorithm

As the path along which ants travel gets closer to the shortest path, a large amount of pheromones accumulate along it, and it is thus recognized as close to the shortest path and selected by ants. However, this kind of path setting leads to congestion in WSNs, and the energy of nodes along the optimal path is exhausted because sensor nodes have a limited amount of energy.

The goal of the CFA proposed in this paper is for nodes to resolve their own congestion and prevent excessive battery consumption in a WSN environment where network resources are limited.

The existing AODV protocol has a mechanism to set new paths and ones with the smallest delays whenever the network topology changes in an environment with high node mobility [9]. It can therefore be said to naturally achieve a balance in data traffic [10].

However, the typical environment where appropriate traffic distribution has not been achieved is one where node mobility is low and the density between nodes is high. Even if traffic congestion occurs, a mechanism for setting new paths is not available, because of which node congestion gradually worsens, and problems occur whereby the increase in end-to-end delays can degrade network performance. To resolve these problems, in the proposed CFA (congestion-free algorithm), once a node determines that excessive traffic is being sent to it, it can transmit a pheromone-PULL message to the source node to give notice of its intention to reject further data relays, so that nodes that receive this message can set new detours. Moreover, the node that transmits the pheromone-PULL message does not relay RREQ (Route Request) messages that arrive from nearby nodes, thus blocking the setting of a new path through the node [11] (Fig. 1).

Figure 2 shows a situation where congestion occurs because excessive traffic is concentrated on Node A and the actions of the congestion-free algorithm to resolve this. Node A is a relay node along the data paths of pairs [S_1, D_1], [S_2, D_2], and [S_3, D_3]. If the amount of traffic sent to Node A reaches a predefined threshold, Node A shifts to a pheromone-PULL state, and to do this, it transmits a pheromone-PULL message as it shifts states. The message goes to the source node that sent the last data packet to Node A (assumed to be S_2 in the figure) to request that a different detour be set. Node S_2 receives the pheromone-PULL message and broadcasts an RREQ to set a new path to Node D_2, and the mechanism of setting the new path is activated.

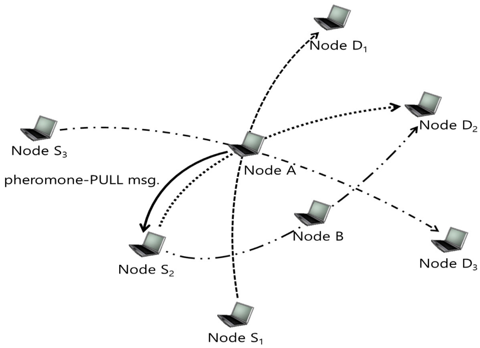

Fig. 1. The basic concept behind congestion-free algorithm.

Table 1. Operational process of CFA.

Algorithm 1: congestion-free algorithm

[When the node A receives a packet]

```
if RREQ message in a packet
if the node A is in pheromone-PULL state
ignore the packet
else
process the packet using the existing routing algorithm
else if pheromone-PULL state
if the pheromone-PULL state is destined to the node A
initiate the route discovery mechanism of the existing routing
algorithm
else
forward the packet with the alternative route
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[At the end of a time interval]

```
if  # of forwarding packets for the time interval ≥ threshold
change the state to pheromone-PULL
send a pheromone-PULL message to the src. of last received
packet
if # of forwarding packets for the time interval < threshold
change the state to normal
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If node S_2 successfully completes the setting of a new detour and data transmission via the new path through a Node B begins, the path that maintains Node A is no longer used. The corresponding entry timer thus expires, and is naturally deleted from the routing table. Node A, which is in a pheromone-PULL state, does not provide packet relay service for RREQ messages sent by S_2 or any other node. The setting of new paths that pass through Node A is thus blocked. In this pheromone-PULL state, if Node A's congestion situation improves and the amount of traffic falls below a given threshold, the node shifts back into a normal state. Table 1 shows the operational process that has been described so far.

The congestion-free algorithm proposed in this paper takes into account the limitations of WSN and focuses on resolving node congestion by balancing traffic. It can resolve the problem of traffic concentration on a particular node, whether node mobility is high or low, and can support load-balancing features through the addition of a simple module to existing routing protocols.

2.2 Performance Evaluation

To execute a simulation using the proposed algorithm to test it, we distributed 500 nodes randomly in a square area with sides of 1000 m (W). Here, the node's communication radius was determined to be $2W/\sqrt{n}$. Considering a network topology where all nodes could connect to a multi-hub, it was assumed that the send/receive scheduling for data aggregation was perfect, and there were no collisions or transmission errors. All nodes periodically generated 100 kbits of sensing data. The channel bandwidth was assumed to be 100 kHz, and the power used to send and receive messages was assumed to be 100 mW. In the simulations, we compared the WiBiA protocol proposed in this paper and the LEACH (Low-energy Adaptive Clustering Hierarchy) protocol, which uses highly energy-efficient routing in WSNs [11].

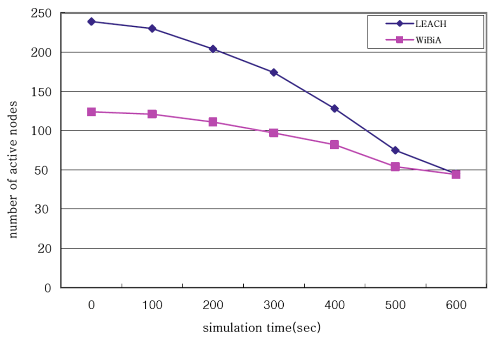

Fig. 2. The number of active nodes during the simulation in LEACH and the proposed WiBiA.

Figure 2 shows the number of active nodes during the simulation time in the existing LEACH and the proposed WiBiA. In the case of LEACH, energy consumption of all nodes was not balanced, and the time point at which energy was exhausted was not fixed so the number of active nodes rapidly decreased. On the other hand, in the case of WiBiA, we can see that all of the nodes consumed energy in a balanced way and maintained the network. WiBiA used alternative routes to re-form a direct path when path disconnection occurred, so the nodes' network delay and energy consumption activities were markedly reduced and the wireless sensor network was continuously maintained. We can see that in the WSN environment with limited network resources, the nodes resolved their own congestion situations and prevented excessive battery use.

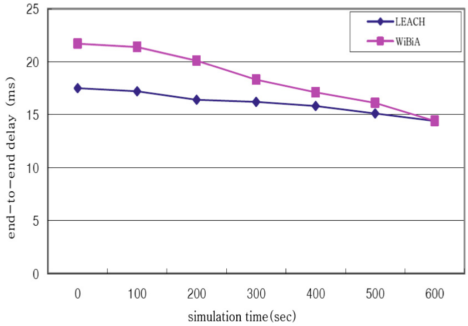

Fig. 3. The time taken to deliver a packet from the source node to the destination node during the simulation in LEACH and the proposed WiBiA.

Figure 3 shows the time taken to deliver a packet from the source node to the destination node. It can be seen that the proposed WiBiA's average delay time increased by 24% compared to LEACH's when the pause time was 0 s and increased by 12% when the pause time was 300 s. This is because when an alternative path is used, the distance of the path between the source node and the destination node becomes longer, and as the pause time grows longer the alternative path usage rate grows lower, so the difference between LEACH and WiBiA average delay times grew smaller. It can be seen that WiBiA shows excellent performance improvements in terms of packet distribution compared to the AODV or LEACH protocols, and therefore if we consider Figs. 2 and 3, we can ease the demand for battery sacrifices by the nodes where traffic is concentrated.

3 Conclusion

In this paper, we have described a biomimicry algorithm designed based on the similarity between biological systems and communication networks to resolve the problems of communication networks. Simulation results show that the proposed routing algorithm has short data collecting times and low energy consumption, and through this it can maximize network energy efficiency.

It can be seen that biomimicry algorithms like WiBiA reliably provide optimal solutions to given problems in complex environments by performing distributed operations according to simple behavioral rules. The rapid path setting and shortest path resetting between moving nodes in WiBiA can be considered the most important element for network lifespan.

Therefore, in order to provide efficient communications between each moving node, a routing method which can effectively and quickly restore disconnected paths is required. We expect that this kind of biomimicry algorithm can be effectively applied to the large-scale communications networks which will appear in the future.

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