The Seventeenth International Symposium on Artificial Life and Robotics 2012 (AROB 17th '12),
B-Con Plaza, Beppu, Oita, Japan, January 19-21, 2012

Data gathering scheme for area monitoring-based wireless sensor networks

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Abstract: Wireless sensor networks have great potential as a means of realizing a wide range of applications, such as natural environmental monitoring, environmental control in residential spaces or plants, and object tracking. As a frame to actualize these sensor applications, this study assumes a monitoring-oriented wireless sensor network, which periodically gathers their sensing data from all sensors placed in a service area. This paper proposes an autonomous decentralized control scheme with data aggregation technique to prolong the lifetime of monitoring-oriented wireless sensor networks. This is a novel scheme devised by considering the application environment of a wireless sensor network as a typical example of a complex system where the adaptive adjustment of the entire system is realized from the local interactions of components of the system. We evaluate our scheme using simulation experiments, and also discuss its development potential.

Keywords: Monitoring, Wireless sensor networks, Multiple sinks, Autonomous decentralized control, Data aggregation.

1 INTRODUCTION

Various communication services are currently considered. They include environmental monitoring or control by static sensors, ad-hoc communication between mobile nodes, and inter-vehicle communication in intelligent transport systems. As a means of facilitating these advanced communication services, autonomous decentralized networks, such as wireless sensor networks [1,2], mobile ad-hoc networks [3-6], and wireless LAN mesh networks [7], have been intensively studied with great interests. Especially, a wireless sensor network, which is a key network to construct ubiquitous information environments, has great potential as a means of realizing a wide range of applications, such as natural environmental monitoring, environmental control in residential spaces or plants, object tracking. Recently, there is growing expectation for a new network service by a novel wireless sensor network consisting of a lot of static sensors arranged in a service area and a few mobile robots as a result of the strong desire for the development of advanced systems that can flexibly function in dynamically changing environments [8].

As a frame to actualize the above-mentioned sensor applications, this study assumes a monitoring-oriented wireless sensor networks composed of many static sensors with global positioning system, which periodically gathers their sensing data from all sensors placed in a service area. In a general monitoring-oriented wireless sensor network, hundreds or thousands of sensors with limited resources, which are compact and inexpensive, are placed in a large scale service area, and the sensing data from each node is gathered to a sink node by inter-node wireless multi-hop communication. Each sensor node consists of a sensing function to measure the status of an observation point or object, a limited function of information processing and a simplified wireless communication function, and it generally operates on a resource with a limited power-supply capacity such as a battery. Therefore, a data gathering scheme and/or a routing protocol capable of meeting the following requirements is needed to prolong the lifetime of wireless sensor networks made up of hundreds or thousands of sensors with limited resources.

1. Efficiency of data gathering
2. Balance of communication load among sensor nodes
3. Adaptability to network topology changes

For the long-term operation of wireless sensor networks, clustering-based schemes [9,10], gradient-based routing protocol [11] and synchronization-based schemes [12-14] are under study, but not all the above requirements are sufficiently satisfied. Recently, bio-inspired routing algorithms, such as ant-based routing algorithms, have attracted a significant amount of interest from plural researchers. In ant-based routing algorithms [15,16], the routing table of each sensor node is updated by applying the process in which ants build routes between their nest and food by chemical substances (pheromones). The advanced ant-based routing algorithm proposed as an example that satisfies the three requirements above is an efficient route-learning algorithm which shares route information between ants (control messages) [17]. In contrast to conventional ant-based routing algorithms, this can suppress the communication load of each sensor node and adapt itself to network topology changes. However, this does not positively ease the communication load concentration on specific sensors, which is the source of problems in the long-term operation of sensor networks. Intensive data transmission to specific sensors results in concentrated energy consumption by them, and causes them to break away from the sensor network early. This makes long-term observation by a wireless sensor network difficult.

In wireless sensor networks, the communication load is concentrated on sensors around a sink node during the operation process. In cases where sensors are not evenly placed in a service area, the communication load is concentrated on sensor nodes placed in a range of low node density. To solve this communication load concentration problem, recent approaches have been to introduce multiple sinks in a wireless sensor network [18,19]. In the fundamental scheme [18], each sensor node sends the sensing data to the nearest sink node. In comparison with the case of one-sink wireless sensor networks, the communication load of sensors around a sink node is reduced. In each sensor node, however, the destination sink node cannot be selected autonomously and adaptively. Therefore, the load of load-concentrated nodes is not sufficiently balanced. The pheromone-oriented routing protocol, which belongs to the category of ant-based routing algorithms, achieves autonomous load-balancing data transmission to multiple sinks, but requires the periodical update of routing table of each sensor node by ants (control messages) dispersed in a wireless sensor network [19]. In monitoring-oriented wireless sensor networks, the nearest sink data transmission scheme in [18] achieves a longer-term operation of the network than the pheromone-oriented routing protocol in [19].

In the previous study [20], we devised a novel autonomous decentralized control scheme and evaluated its fundamental performance through simulation experiments. This scheme needs no special communication for network control, but enables autonomous load-balancing data transmission to multiple sinks. The load of each sensor node is autonomously balanced. In monitoring-oriented wireless sensor networks, however, the efficiency of data gathering should be improved. In this paper, we propose an autonomous decentralized control scheme with data aggregation technique for the long-term of monitoring-oriented wireless sensor networks, and evaluate the proposed scheme using simulation experiments in detail. The rest of this paper is organized as follows. First, in Sec.2, the proposed scheme is detailed, and its novelty and superiority are described. In Sec.3, the experimental results are reported in detail, and the effectiveness of the proposed scheme is demonstrated by comparing its performances with those of the existing scheme. Finally, we give the overall conclusion and future problem of this study in Sec.4.

2 PROPOSED SCHEME

To facilitate the long-term operation of an actual sensor network service, recent approaches have been to introduce multiple sinks in a wireless sensor network. In wireless sensor networks with multiple sinks, the sensing data of each node is generally allowed to gather at any of the available sinks. The proposed scheme devised by considering the application environment of a wireless sensor network as a typical example of a complex system where the adaptive adjustment of the entire system is realized from the local interactions of components of the system is a novel data gathering scheme based on this assumption, which can be expected to produce a remarkable effect in monitoring-oriented wireless sensor networks with multiple sinks.

2.1 Construction of a data gathering environment

Each sink node has a connective value named a "value to self", which is not updated by transmitting a control packet and receiving data packets. In the initial state of monitoring-oriented wireless sensor network with multiple sinks, each sink node broadcasts a control packet containing its own ID and "value to self", and hop counts (=*0*). This control packet is rebroadcast throughout the sensor network with hop counts updated. By receiving the control packet from each sink node, each sensor node can grasp the "value to self" of each sink node, and the IDs and the hop counts from each sink node of its own neighboring nodes.

Initial connective value of each sensor node, which is the connective value before starting data transmission, is generated by using the "value to self" of each sink node and the hop counts from each sink node. The procedure for computing initial connective value of a node (i) is as follows:

1. The value [$v_{ij}(0)$] on each sink node (j = 1, … , S) of node (i) is first computed according to the following equation

$$v_{ij}(0) = vo_j \times dr^{hops_{ij}} \quad (j = 1,\dots,S) \tag{1}$$

   where vo_j (j =1, … , S) is the "value to self" of sink node (j), $hops_{ij}$ is the hop counts from sink node (j) of node (i). dr represents the value attenuation factor accompanying the hop determined within the interval [0,1].

2. Then, the initial connective value $[v_i(0)]$ of node (i) is generated as follows

$$v_i(0) = \max v_{ij}(0) \qquad (j = 1, \ldots, S) \tag{2}$$

where this connective value $[v_i(0)]$ can be also conducted from the following equation

$$v_i(0) = vm_i(0) \times dr \tag{3}$$

In (3), $vm_i(0)$ represents the greatest connective value before starting data transmission in the neighborhood nodes of node (i).

Before starting data transmission, each sensor node computes the initial connective value of each neighborhood node according to the above (1) and (2), and stores the computed connective value, which is used as the only index to evaluate the relay destination value of each neighboring node, in each neighborhood node field of its own routing table. Therefore, the routing table of each sensor node, which is made up of the IDs and initial connective values before starting data transmission to neighboring nodes, is constructed.

2.2 Data transmission and connective value update

For data transmission, each sensor node selects the neighboring node with the greatest connective value from its own routing table as a relay node, and transmits the data packet to this selected node. In cases where more than one node shares the greatest connective value, however, the relay node is determined between them at random. The data packet in each sensor node is not sent to a specified sink node. By repetitive data transmission to the neighboring node with the greatest connective value, data gathering at any of the available sinks is completed. In the proposed scheme, the connective value of each sensor node is updated by considering residual node energy. Therefore, by repetitive data transmission to the neighboring node with the greatest connective value, the data transmission routes are not fixed.

To realize autonomous load-balancing data transmission, the data packet from each sensor node includes its own updated connective value. Here, we assume that a node (l) receives a data packet at time (t). Before node (l) relays the packet, it replaces the value in the connective value field of the data packet by its own renewal connective value computed according to the following connective value update equation

$$v_l(t) = vm_l(t) \times dr \times {e_l(t)}/{E_l} \tag{4}$$

where $vm_l(t)$ is the greatest connective value at time (t) in the routing table of node (l), and $e_l(t)$ and E_l represent the residual energy at time (t) of node (l) and the battery capacity of node (l), respectively.

In our scheme, the data packet addressed to the neighboring node with the greatest connective value is intercepted by all neighboring nodes. This packet includes the updated connective value of the source node based on (4). Each neighborhood node that intercepts this packet stores the updated connective value in the source node field of its own routing table. **Fig.1** shows an example of data packet transmission and its accompanying connective value update. In this example, node (l) refers to its own routing table and addresses the data packet to node (r), which has the greatest connective value $[vm_l(t)]$. When this data packet is intercepted, each neighboring node around node (l) stores the updated connective value $[v_l(t)]$ included in the data packet in the node (l) field of its own routing table.

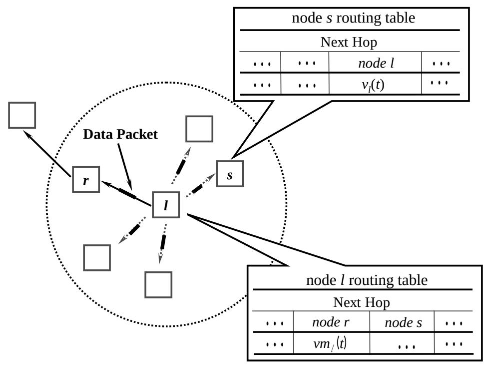


Fig.1. Data transmission and connective value update

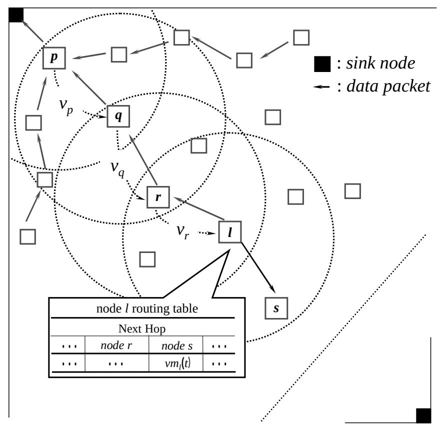


Fig.2. Autonomous load-balancing data transmission to multiple sinks

The proposed scheme requires the construction of a data gathering environment in the initial state of wireless sensor networks with multiple sinks, but needs no special communication for network control. The above-mentioned simple mechanism alone achieves autonomously adaptive load-balancing data transmission to multiple sinks, as in **Fig.2.** It can be expected that the lifetime of wireless sensor networks is extended by reducing the communication load for network control and solving the node load concentration problem.

2.3. Autonomous data aggregation technique

To improve the efficiency of data gathering, an autonomous data aggregation technique is newly introduced in our scheme. This data aggregation technique matches our autonomous decentralized control scheme. Generally, data aggregation-based schemes improve the efficiency of data gathering in a wireless sensor network, but some of them facilitate the communication load concentration on specific sensors and/or limited routes [2]. Since our scheme has the mechanism to realize autonomous load-balancing data transmission to multiple sinks using many routes, however, it can be considered that to introduce a data aggregation technique in our autonomous decentralized control scheme is effective.

The data aggregation to improve the efficiency of data gathering is autonomously actualized without special communication in the operation process of a wireless sensor network. In our data aggregation technique, the node that first transmits the original data packet or the data packet from the other sensor node to the neighboring node with the greatest connective value in the node itself and its own neighboring nodes becomes a data aggregation node called *head node*, and functions for efficient data gathering. Here, the neighboring node that intercepts the data packet from a head node becomes the member of the head node in cases where it is not the member of any of the other head nodes, and the connective value of the head node is greater than its own connective value. When the node that is the member of a head node transmits the data packet to any of its own neighboring nodes, it addresses the data packet to the head node. **Fig.3** shows an example of efficient data gathering by our data aggregation technique. In **Fig.3**, node (l) and node (r) are head nodes, and node (s) is the member of head node (l). In this example, node (l) transmits the data aggregation packet containing the sensing data from each member to the node (r) with the greatest connective value in its own neighboring nodes.

In addition, the function to ease the continuous communication load concentration to head nodes is introduced in our data aggregation technique. The node that is the member of a head node breaks away from the member when the connective value of the head node became less than its own connective value in the network operation process, and it becomes a new head node, and newly functions for efficient data gathering in cases where the other head node, the connective value of which is greater than its own connective value, does not exist in its own neighboring nodes. On the other hand, it becomes the member of the other head node with the greatest connective value in cases where the other head nodes, the connective values of which are greater than its own connective value, exist in its own neighboring nodes. **Fig.4** illustrates an example of this additional function. In **Fig.4**, node (l) and node (r) are head nodes, as in **Fig.3**. In this example, node (s) breaks away from the member of head node (l) because the connective value of head node (l) became less than its own connective value. Here, node (s) becomes a new head node when the connective value of head node (r) is less than its own connective value, as shown in **Fig.4**(a), and becomes the member of node (r) when the connective value of head node (r) is greater than its own connective value, as shown in **Fig.4**(b).

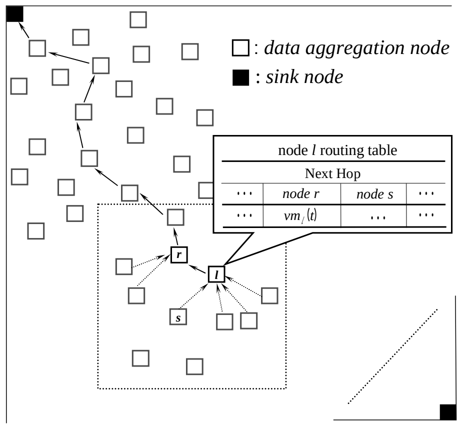
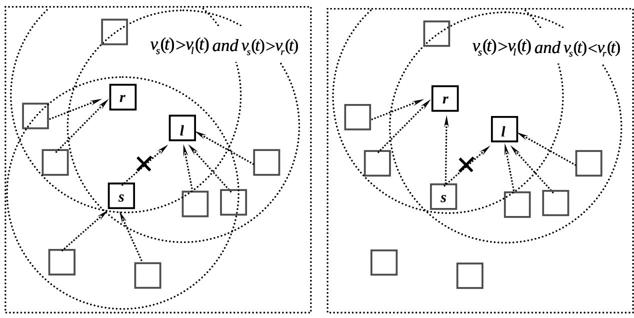


Fig.3. An example of data aggregation



(a) Case1 (b) Case2

Fig.4. An example of additional function

3 SIMULATION EXPERIMENTS

Through simulation experiments on monitoring-oriented wireless sensor networks, the performances of our autonomous decentralized control scheme with data aggregation technique is investigated in detail to verify its effectiveness.

In a large scale and dense wireless sensor network with multiple sinks made up of many static sensors placed in a large scale square field, it is assumed that each sensor node constructing the network transmits the data packet with the measurement data periodically. The conditions of the simulation which were used in the experiments performed are shown in **Table1**. In the initial state of the simulation experiments, many static sensors are randomly arranged in the set experimental area, and two sinks are placed on the corners of this area. An example of the arrangement of sensors in the set experimental area is illustrated in **Fig.6**. In the experiments performed, the value attenuation factor accompanying hop（*dr*）and the "value to self" of each sink node introduced in the proposed scheme were set to 0.5 and 100.0, respectively. The sizes of the control packets were set to 36 bytes and the sizes of the data packets were set to $40+10\times n$ bytes, where the size of sensing data of each node was set to 10 bytes, and *n* represents the number of sensing data in each data packet. The battery capacity of each sensor node was modeled as 0.5J, and the energy consumption of each sensor node was computed as in［9］.

Table 1. Conditions of simulation

Simulation size	*2,400 m ✕ 2,400 m*
Number of sensor nodes	*1,000*
Range of radio wave	*150 m*
Number of sinks	*2*

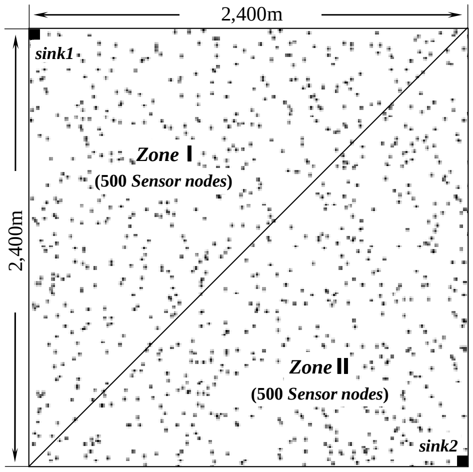
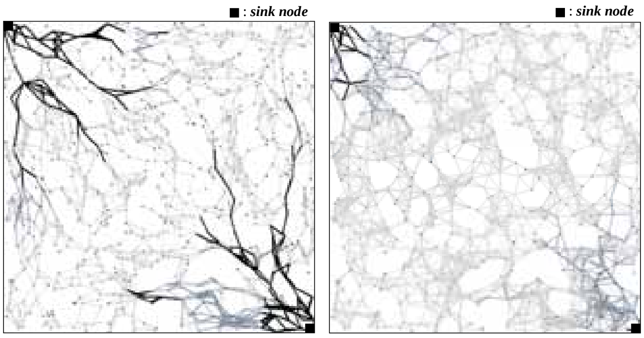


Fig.5. Arrangement of sensors in the set experimental area（Case1）

The proposed scheme is evaluated through a comparison with the existing one［18］, which describes representative data gathering for wireless sensor networks with multiple sinks. In the experimental results reported, the scheme in［18］is denoted as "Nearest Sink". First, the experimental results on the arrangement of sensors（Case1）illustrated in **Fig.5** is shown. **Fig.6**（a）and（b）illustrate the routes used by applying Nearest Sink and the proposed scheme, where the bold lines in these figures indicate the routes frequently used. From **Fig.6**, it is confirmed that the proposed scheme can balance and improve the load of each sensor node by the autonomous load-balancing data transmission mechanism and the data aggregation technique newly introduced. **Fig.7** shows the transition of the delivery ratio of the total number of sensing data periodically transmitted from each sensor node. In **Fig.7**, our scheme without data aggregation is denoted as "Proposal A", and our scheme with data aggregation technique is as "Proposal B". From **Fig.7**, it can be confirmed that the proposed scheme achieves a longer-term operation of a monitoring-oriented wireless sensor network than Nearest Sink, and the effect of our scheme is facilitated by the autonomous data aggregation technique newly introduced in this study.



（a）Nearest Sink （b）Proposal

Fig.6. Routes used by applying Nearest Sink or the proposed scheme

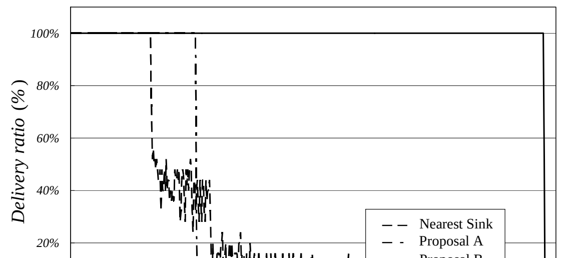


Fig.7. Delivery ratio（Case1）

Next, we assume the cases where sensors are not evenly placed in the set experimental area, as in **Figs.8**（Case2）. **Fig.9** shows the transition of the delivery ratio of the total number of sensing data periodically transmitted from each sensor node, as in **Fig.7**. Through the experimental results, it can be also confirmed that our scheme with data aggregation technique is substantially advantageous for the long-term operation of monitoring-oriented wireless sensor networks with multiple sinks.

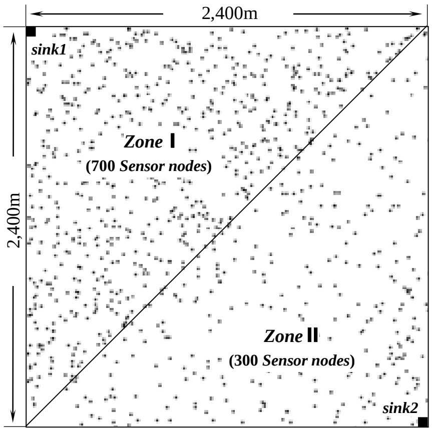


Fig.8. Arrangement of sensors（Case2）

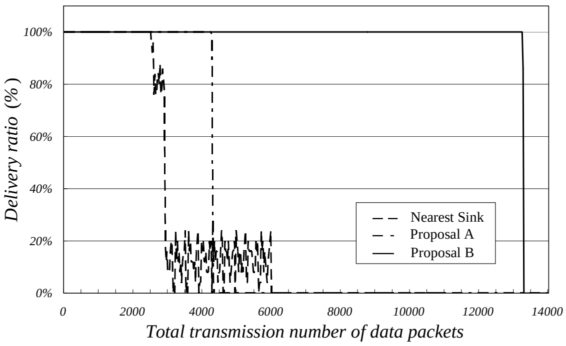


Fig.9. Delivery ratio（Case2）

4 CONCLUSION

In this paper, an autonomous decentralized control scheme with data aggregation technique that adaptively reduces the load of load-concentrated sensors and facilitates the long-term operation of monitoring-oriented wireless sensor networks with multiple sinks has been proposed. This is a novel scheme devised by considering the application environment of a wireless sensor network to be a typical example of a complex system where the adjustment of the entire system is adaptively realized from the local interactions of components of the system. In simulation experiments, the performances of the proposed scheme were compared with those of the existing one. The experimental results indicate that the proposed scheme is superior to the existing one from the viewpoint of the long-term operation of monitoring-oriented wireless sensor networks. Future work includes a detailed evaluation of the proposed scheme in various network environments.

REFERENCES

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, Wireless sensor networks: A survey, *Computer Networks Journal*, Vol.38, No.4, pp.393-422, 2002.

[2] R. Rajagopalan and P. K. Varshney, Data aggregation techniques in sensor networks: A survey, *IEEE Communications Surveys and Tutorials*, Vol.8, pp.48-63, 2006.

[3] C. E. Perkins and E. M. Royer, Ad hoc on-demand distance vector routing, *Proc. of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pp.90-100, 1999.

[4] D. B. Johnson, D. A. Maltz, Y. C. Hu and J. G. Jetcheva, The dynamic source routing protocol for mobile ad hoc networks, *IETF Internet Draft, draft-ietf-manet-dsr-09.txt*, 2003.

[5] T. Clausen and P. Jaquet, Optimized link state routing protocol, *Request for Comments 3626*, 2003.

[6] R. Ogier, M. Lewis and F. Templin, Topology dissemination based on reverse-path forwarding（TBRPF）, *IETF Internet Draft, draft-ietf-manet-tbrpf-10.txt*, 2003.

[7] S. Sakata, H. Aoki and K. Mase, Mobile ad hoc networks and wireless LAN mesh networks, *IEICE Trans. Commun.*, Vol.E89-B, No.6, pp.811-823, 2006.

[8] K. Matsumoto, A. Utani and H. Yamamoto, Adaptive and efficient routing algorithm for mobile ad-hoc sensor networks, *ICIC Express Letters*, Vol.3, No.3（B）, pp.825-832, 2009.

[9] W. R. Heinzelman, A. Chandrakasan and H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, *Proc. of the Hawaii International Conference on System Sciences*, pp.3005-3014, 2000.

[10] Y. Jin, J. Jo and Y. Kim, Energy-efficient multi-hop communication scheme in clustered sensor networks, *International Journal of Innovative Computing, Information and Control*, Vol.4, No.7, pp.1741-1749, 2008.

[11] L. Xia, X. Chen and X. Guan, A new gradient-based routing protocol in wireless sensor networks, *Lecture Notes in Computer Science*, Vol.3605, pp.318-325, 2004.

[12] N. Wakamiya and M. Murata, Synchronization-based data gathering scheme for sensor networks, *IEICE Trans. Commun.*, Vol.E88-B, No.3, pp.873-881, 2005.

[13] H. Nakano, A. Utani, A. Miyauchi and H. Yamamoto, Data gathering scheme using chaotic pulse-coupled neural networks for wireless sensor networks, *IEICE Trans. Fundamentals*, Vol.E92-A, No.2, pp.459-466, 2009.

[14] H. Nakano, A. Utani, A. Miyauchi and H. Yamamoto, Chaos synchronization-based data transmission scheme in multiple sink wireless sensor networks, *International Journal of Innovative Computing, Information and Control*, Vol.7, No.4, pp.1983-1994, 2011.

[15] D. Subramanian, P. Druschel and J. Chen, Ants and reinforcement learning: A case study in routing in dynamic networks, *Technical Report TR96-259*, Rice University, 1998.

[16] Y. Ohtaki, N. Wakamiya, M. Murata and M.Imase, Scalable and efficient ant-based routing algorithm for ad-hoc networks, *IEICE Trans. Commun.*, Vol.E89-B, No.4, pp.1231-1238, 2006.

[17] A. Utani, E. Orito, A. Kumamoto and H. Yamamoto, An advanced ant-based routing algorithm for large-scale mobile adhoc sensor networks, *Trans. SICE*, Vol.44, No.4, pp.351-360, 2008.

[18] E. I. Oyman and C. Ersoy, Multiple sink network design problem in large scale wireless sensor networks, *Proc. of the 2004 International Conference on Communications*, Vol.6, pp.3663-3667, 2004.

[19] E. Orito, A. Utani and H. Yamamoto, Pheromone-oriented routing protocol for load balancing of wireless sensor networks with multiple sinks, *Journal of SOFT*, Vol.21, No.1, pp.56-68, 2009.

[20] K. Matsumoto, A. Utani and H. Yamamoto, Bio-inspired data transmission scheme to multiple sinks for the long-term Operation of wireless sensor networks, *Int. J. Artificial Life and Robotics*, Vol.15, No.2, pp.189-194, 2010.
