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ORIGINAL ARTICLE

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Bio-inspired data transmission scheme to multiple sinks for the long-term operation of wireless sensor networks

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Abstract Wireless sensor networks have a wide range of applications, such as natural environmental monitoring, object tracking, and environmental control in residential spaces or plants. In wireless sensor networks, many sensor nodes with limited resources are placed in an observation area and used to gather information about environments. Therefore, a data gathering scheme (or a routing algorithm) for saving and balancing the energy consumption of each sensor node is needed to prolong the lifetime of wireless sensor networks. This article proposes a new bio-inspired data transmission scheme for the long-term operation of wireless sensor networks. By using the proposed scheme, autonomous load-balancing data transmission to multiple sinks can be actualized. We evaluate the proposed scheme using computer simulations to verify its effectiveness, and also discuss its development potential.

Key words Wireless sensor networks · Multiple sinks · Data gathering · Autonomous load-balancing

1 Introduction

Wireless sensor networks have a wide range of applications, such as natural environmental monitoring, object tracking, and environmental control in residential spaces or plants.[1,2] In wireless sensor networks, generally hundreds or thousands of static sensor nodes, which are compact and inexpensive, are placed in a large-scale observation area, and 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 (temperature, humidity, motion, etc.) 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 (or a routing algorithm) capable of meeting the following requirements is needed to prolong the lifetime of wireless sensor networks.

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

As data-gathering schemes for the long-term operation of wireless sensor networks, clustering-based data gathering,[3] and synchronization-based data gathering[4,5] are under study, but not all the above requirements are satisfied. Recently, bio-inspired routing algorithms, such as ant-based routing algorithms, have attracted a significant amount of interest from many researchers as examples that satisfy the three requirements above. In ant-based routing algorithms,[6] the routing table of each sensor node is generated and updated by applying the process in which ants build routes between their nest and food using chemical substances (pheromones). The advanced ant-based routing algorithm in Utani et al.[7] is an efficient route-learning algorithm which shares route information between control messages (ants). 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 sensor nodes, which is the source of problems in the long-term operation of wireless sensor networks. Intensive data transmission to specific sensor nodes results in concentrated energy consumption by them, and causes them to break away from the network early. This makes long-term observation by a wireless sensor network difficult.

In wireless sensor networks, the communication load is generally concentrated on sensor nodes around a sink node during the operation process. In cases where sensor nodes

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are not placed evenly in an observation area, the communication load is concentrated on sensor nodes placed in an area of low node density. To solve this communication load concentration problem, a data-gathering scheme for wireless sensor networks with multiple sinks has been proposed.[8,9] In this scheme, each sensor node sends sensing data to the nearest sink node. In comparison with the case of one-sink wireless sensor networks, the communication load of sensor nodes around a sink node is reduced. In each sensor node, however, the destination (sink) node cannot be selected autonomously and adaptively.

This article proposes a new bio-inspired data transmission scheme that adaptively reduces the load of load-concentrated nodes and facilitates the long-term operation of wireless sensor networks with multiple sinks. The proposed scheme has autonomous load-balancing data transmission 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. In the proposed scheme, the load of each sensor node is autonomously balanced. The rest of this article is organized as follows. In Sect. 2, the proposed scheme is detailed, and its novelty and superiority are described. In Sect. 3, the results of simulation experiments are reported, and the effectiveness of the proposed scheme is demonstrated by comparing its performances with those of existing schemes. Finally, we give our conclusions and ideas for further study in Sect. 4.

2 Proposed scheme

Wireless sensor networks are generally used to observe or monitor the status of an object area. To facilitate the long-term operation of an actual sensor network service, a recent approach has been to introduce multiple sinks in a wireless sensor network.[8,9] In a wireless sensor network with multiple sinks, the sensing data of each node is generally allowed to gather at any of the available sinks. The proposed scheme is a new bio-inspired data transmission scheme based on this assumption, which can be expected to produce a remarkable effect in multiple-sink wireless sensor networks. In this study, a large-scale wireless sensor network with multiple sinks made up of hundreds or thousands of static sensor nodes with limited resources is assumed.

2.1 Construction of a data-gathering environment

Each sink node has a pheromone value named a "value to self," which is not updated by transmitting a control packet and receiving data packets. In the proposed scheme, the "value to self" of each sink node is dispersed throughout the network before the observation of the object area is started. In each sensor node, the pheromone value computed from the "value to self" is used as the only index to evaluate the relay destination value of each neighborhood node.

In the initial state of a multiple-sink and large-scale wireless sensor network, each sink node locally broadcasts a control packet composed of its own ID and "value to self". Each sensor node that receives this control packet performs the following processing, and locally broadcasts the newly generated control packet.

1. A node (l) that receives a control packet first stores the pheromone value included in the packet in the source node field of its own routing table. On receiving plural control packets from the same source node, the greatest pheromone value in their control packets is stored. If the source node is a sink node, the "value to self" is stored. This processing is executed whenever a control packet is received.
2. As a piece of information included in the newly generated control packet, node (l) then computes its own pheromone value ($v_l(0)$) according to the equation

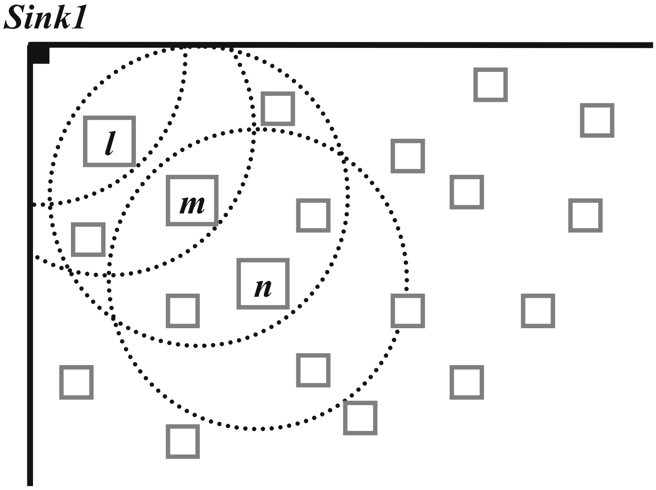
$$v_l(0) = vmax_l(0) \times dr_{hop} \quad (0 < dr_{hop} < 1) \tag{1}$$

where $vmax_l(0)$ and dr_{hop} represent the greatest pheromone value before starting data transmission in the routing table of node (l) and the pheromone value attenuation factor accompanying the hop determined within the interval [0,1], respectively. Then, a new control packet composed of its own ID (l) and computed pheromone value ($v_l(0)$) is locally broadcast. Also, the control packet containing the recomputed pheromone value based on Eq. 1 is locally rebroadcast if the greatest pheromone value in the routing table of node (l) was updated by receiving a new control packet after the above control packet was locally broadcast.

In Fig. 1, an example of pheromone dispersion from a sink node (*Sink1*) is shown when the "value to self" with a sink node (*Sink1*) and the pheromone value attenuation factor accompanying the hop (dr_{hop}) were set to 100.0 and 0.5, respectively. By executing the above processing at appropriate time intervals in each sensor node, the routing table of each sensor node, which is made up of the IDs and initial pheromone values before starting data transmission to neighboring nodes, is constructed.

2.2 Data transmission and pheromone value update

For data packet transmission, each sensor node selects the neighboring node with the greatest pheromone 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 share the greatest pheromone 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 pheromone value, data gathering at any of the available sinks is completed. In the proposed scheme, the pheromone value of each sensor node is updated by considering residual node energy. Therefore, by repetitive data transmission to the neighboring node with the greatest pheromone value, the data transmission routes are not fixed.



node l routing table

Next Hop		
Sink1	*node m*	. . .
100.0	25.0	. . .

node m routing table

Next Hop		
node l	*node n*	. . .
50.0	12.5	. . .

node n routing table

Next Hop		
node m	. . .	. . .
25.0	. . .	. . .

Fig. 1. An example of pheromone dispersion from a sink node (*Sink 1*)

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

$$v_l(t) = vmax_l(t) \times dr_{hop} \times dr_{lec}(t) \quad \left(0 < dr_{hop} < 1\right) \tag{2}$$

$$dr_{lec}(t) = e_l(t)/E_l \tag{3}$$

where $vmax_l(t)$ is the greatest pheromone 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 the proposed scheme, the data packet addressed to the neighboring node with the greatest pheromone value is intercepted by all neighboring nodes. This data packet includes the updated pheromone value of the source node based on Eqs. 2 and 3. Each neighborhood node that intercepts this packet stores the updated pheromone value in the source node field of its own routing table. Figure 2 shows an example of data packet transmission and its accompanying pheromone 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 pheromone value ($vmax_l(t)$). When this data packet is intercepted, each neighboring node around node (l) stores the updated pheromone value ($v_l(t)$) included in the data packet in the node (l) field of its own routing table.

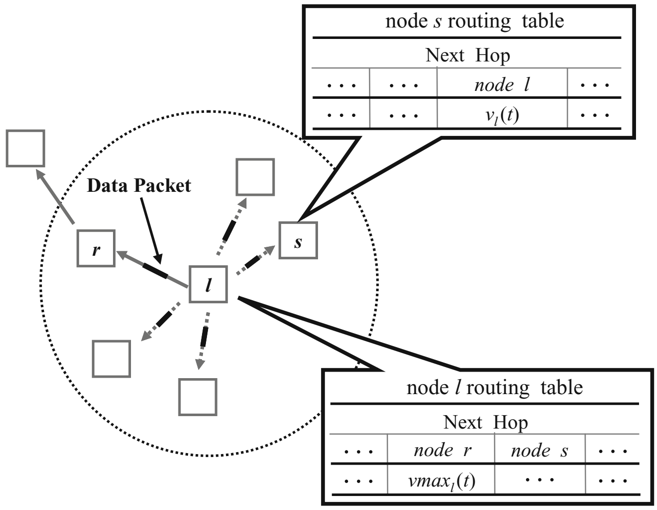


Fig. 2. Data transmission and pheromone value update

The proposed scheme requires the construction of a data-gathering environment in the initial stage of a multiple-sink and large-scale wireless sensor network, 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. 3. The lifetime of wireless sensor networks can be extended by reducing the communication load for network control and solving the node load-concentration problem.

3 Simulation experiment

Through simulation experiments on a wireless sensor network with multiple sinks, the performance of the proposed scheme is investigated in detail to verify its effectiveness.

3.1 Conditions of simulation

In a wireless sensor network with multiple sinks consisting of many static sensor nodes placed in a large-scale observation area, only sensor nodes that detected abnormal data set were assumed to transmit the measurement data. The conditions of the simulation which were used in the experiments performed are shown in Table 1. In the initial state

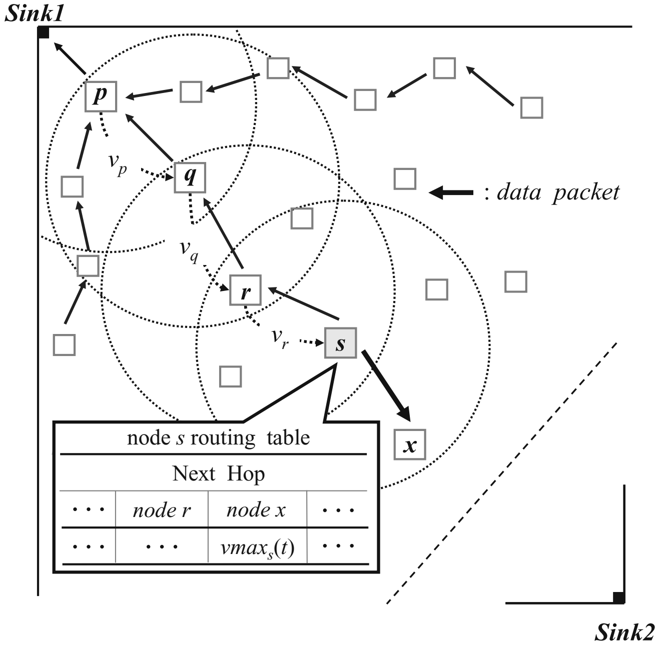


Fig. 3. An example of autonomous load-balancing data transmission to multiple sinks

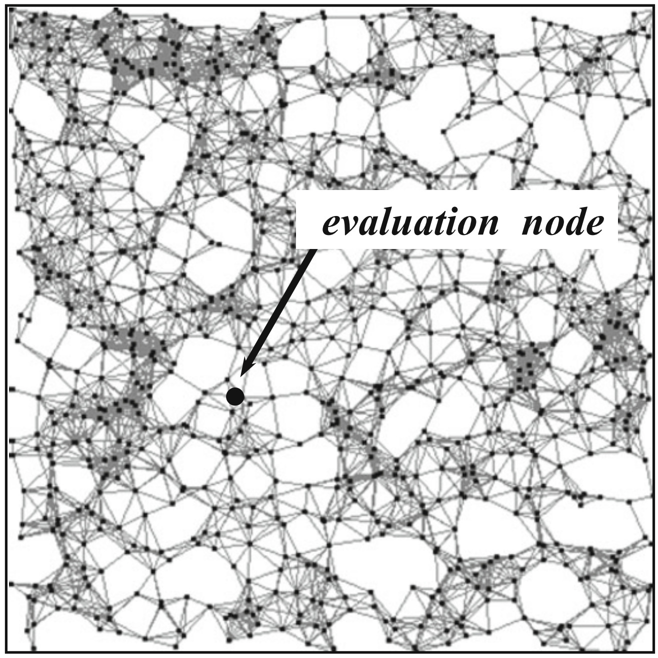


Fig. 4. A wireless sensor network consisting of many static sensor nodes

Table 1. Conditions of simulation

Simulation size	2400 m × 2400 m
Number of sensor nodes	1000
Range of ratio wave	150 m
Number of sinks	2 or 3

of the simulation experiments, static sensor nodes are randomly arranged in the set simulation area, and multiple sinks are placed on the boundaries containing the corners of this area. The network configuration is illustrated in Fig. 4. In the experiments performed, the "value to self" of each sink node and the pheromone value attenuation factor accompanying hop (dr_{hop}) introduced in the proposed scheme were set to 100.0 and 0.5, respectively. The sizes of the data packets and those of the control packets were set to 18 bytes and 6 bytes, respectively. The battery capacity (E) of each sensor node was set to 0.5 J.

In the experimental results reported, the proposed scheme is evaluated through a comparison with existing ones[6–9] where the parameter settings that produced good results in a preliminary investigation[10] were adopted in preference to existing ones.

3.2 Experimental results

In the first experiment, it was assumed that the evaluation node marked in Fig. 4 detected an abnormal value and transmitted the data packet with this abnormal value periodically. The routes used by applying the proposed scheme are shown in Figs. 5 and 6, where these figures indicate the routes used in the simulation model with two sinks and those in the simulation model with three sinks, respectively. In Figs. 5 and 6, of the 3000 data packets transmitted from the evaluation node, the routes used by the first 300 data packets are illustrated in (1), those used by the 1000 data packets are in (2), those used by the 2000 data packets are in (3), and those used by a total of 3000 data packets are in (4). From Figs. 5 and 6, it can be confirmed that the proposed scheme enables the autonomous load-balancing transmission of data packets to multiple sinks using multiple routes.

Next, it was assumed that data packets were periodically transmitted from a total of 20 sensor nodes placed in the set simulation area. In Fig. 7, the transition of the delivery ratio of the total number of data packets transmitted from a total of 20 randomly selected sensor nodes is shown, and the lifetime of the simulation model with two sinks, as in Fig. 5, is compared. In Fig. 7, the existing schemes in Ohtaki et al.[6] and Utani et al.,[7] which belong to the category of ant-based routing algorithms, are denoted as *MUAA* and *AAR*, respectively. The existing schemes in Oyman and Ersoy[8] and Ferriere et al.,[9] which describe representative data gathering for a wireless sensor network with multiple sinks, are denoted as *NS*. From Fig. 7, it can be confirmed that the proposed scheme achieves a longer-term operation of a wireless sensor network with multiple sinks than the existing ones because it improves and balances the load of each sensor node by the communication load reduction for network control and the load-balancing data transmission. Through simulation experiments, it was verified that the proposed scheme is substantially advantageous for the long-term operation of a multiple-sink wireless sensor network.

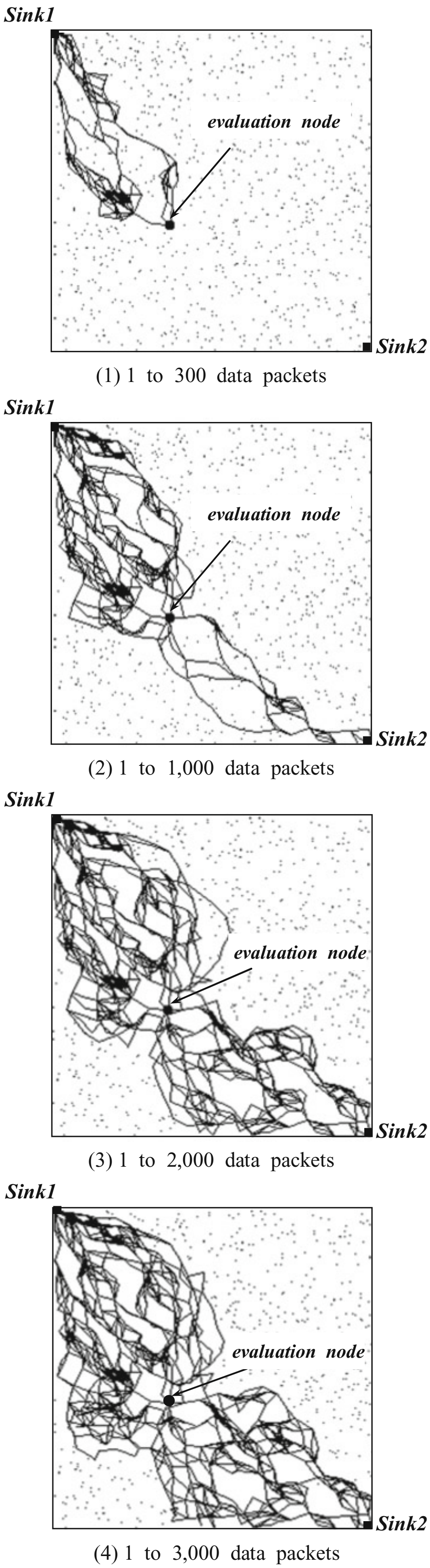


Fig. 5. Routes used by applying the proposed scheme to the simulation model with two sinks

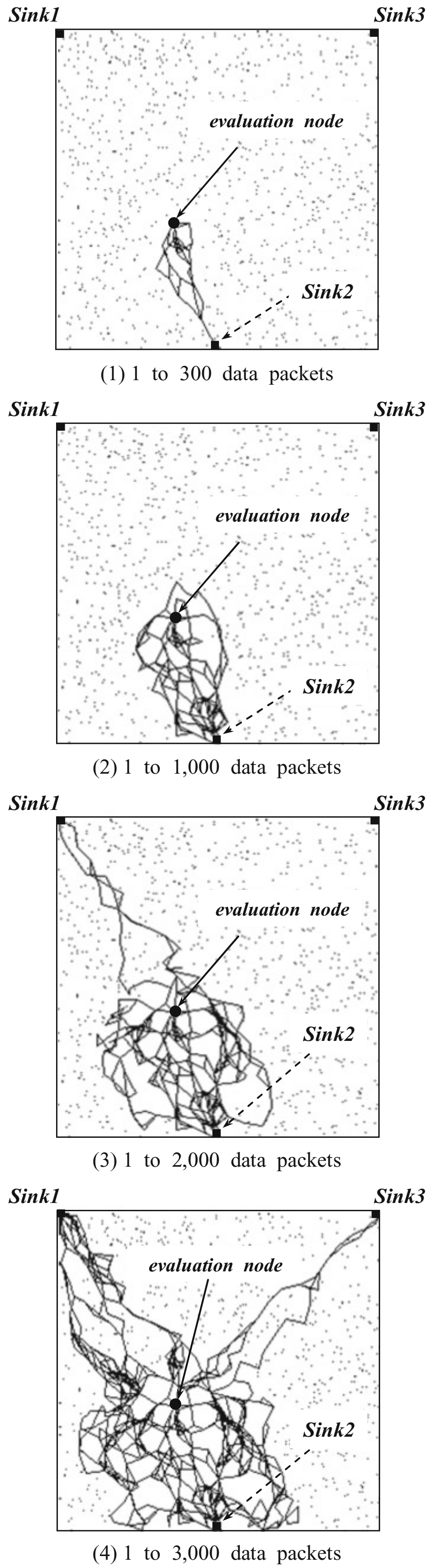


Fig. 6. Routes used by applying the proposed scheme to the simulation model with three sinks

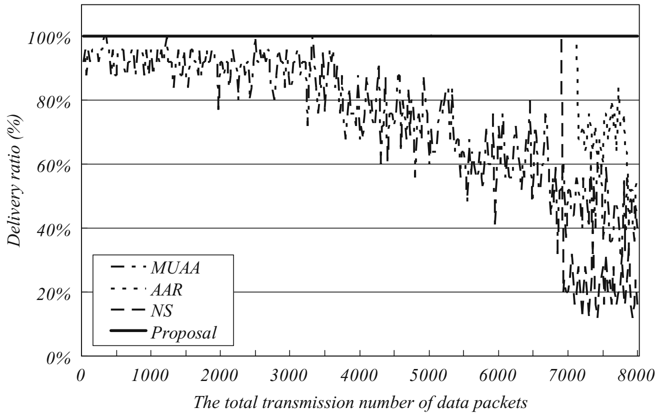


Fig. 7. Transition of delivery ratio

4 Conclusions

Here, a new bio-inspired data transmission scheme to multiple sinks for the long-term operation of wireless sensor networks has been proposed. This is an autonomous load-balancing data transmission scheme devised by considering the application environment of a wireless sensor network to be a typical example of a complex system,. In simulation experiments, the performances of the proposed scheme were compared with those of existing ones. The experimental results indicate that the proposed scheme is superior to the existing ones from the viewpoint of the long-term operation of wireless sensor networks. Future work includes a detailed evaluation of the parameters introduced in the proposed scheme and various network sizes.

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