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Recommended Paper

HGAF: A Power Saving Scheme for Wireless Sensor Networks

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The sensor nodes of wireless sensor networks are placed in observation areas and transmit data to the observer by using multi-hop communication between nodes. Because these nodes are small and have a limited power supply, they must save power in order to prolong the network's lifetime. We propose HGAF (Hierarchical Geographic Adaptive Fidelity) to give a layered structure to GAF (Geographic Adaptive Fidelity), a power saving technique using location information in sensor networks. Simulation results reveal that HGAF outperforms GAF in terms of the number of survived nodes and packet delivery ratio when the node density is high. The lifetime of dense and randomly distributed sensor networks with HGAF is about 200% as long as ones with GAF.

1. Introduction

Wireless sensor networks (WSNs) have been the focus of a lot of recent research and development. In WSNs, wireless sensor nodes are placed in observation areas and transmit sensing data to the observer by using multi-hop communication between nodes. Because wireless sensor nodes are small and have a limited power supply, it is important for them to be energy efficient. Various studies on power saving algorithms for WSNs have been done.

Adaptive fidelity algorithms keep the fidelity of network reachability constant while adapting the nodes' behavior in a way that extends the network's lifetime [1]. Geographic Adaptive Fidelity (GAF) [2], GAF-h [3], and SPAN [4] are well-known adaptive fidelity algorithms. GAF saves power by making some nodes in WSNs sleep autonomously on the basis of their position and residual energy. In GAF, sensor nodes are divided into groups on a virtual grid and only one node in each group works as the active node that is always on and forwards packets between groups. The power-saving ability of GAF is limited by the grid layout and the communication range of sensor nodes. GAF-h is a technique to improve connectivity between nodes while maintaining the power saving performance of GAF. It uses hexagonal geographical cells to group sensor nodes, while GAF uses square ones. SPAN saves power by reducing the number of active nodes on the network by enabling nodes to make their own (i.e., local) decisions based on the number of neighbor nodes and residual energy. It does not use geographical information for this operation, while GAF and GAF-h use such information.

Studies have also been done on other types of power saving algorithms besides adaptive fidelity algorithms. First, there are many MAC-layer power saving approaches. For example, Ye proposed S-MAC [5], a low power MAC protocol for WSNs. S-MAC uses idle listening by making nodes constantly switch between two periodic states: sleep and active. During the active state, nodes either listen for any communication addressed to them or initiate communication themselves. Dam proposed T-MAC [6], an expanded version of S-MAC. T-MAC improves on S-MAC's energy consumption by using a very short listening window at the beginning of each active period. This period is used to send or receive RTS and CTS packets. Buettner proposed X-MAC [7], a low-power MAC protocol for WSNs. X-MAC employs a strobed preamble approach by transmitting a series of short preamble packets, each containing the address information of the target receiver.

There are also cluster-based approaches which select cluster head nodes which are in charge of aggregating and forwarding packets from the members of the clusters so that the energy consumption required for the data transmission to the sink node can be small. For example, Heinzelman proposed LEACH, an energy-efficient protocol architecture for a clustered sensor network [8]. In LEACH, each node in the network becomes a cluster head according to a certain probability so that a suitable number of nodes can be cluster heads. In LEACH, cluster heads are in charge of forwarding data to a sink node using direct communica-

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tion. Younis proposed HEED, whereby cluster heads are periodically selected according to a hybrid method involving their residual energy and a secondary parameter, such as proximity between the neighbors and node degree [9]. GAF also can be categorized as a clustering technique. The biggest difference between GAF and other clustering techniques like LEACH and HEED, etc. is that GAF uses the information of geographical positions of nodes to form clusters keeping the connectivity between them, while other techniques do not use geographical information.

Furthermore, various techniques for power saving in sensor networks have been proposed. For example, reducing the transmission of redundant data is useful. Chen proposed a scheme that uses metadata to reduce the traffic on sensor networks [10]. In this scheme, only one of the sensor nodes within the sensing range of an event in a cluster is selected through negotiations using metadata to transmit the sensing data to the cluster head. Using mobility of nodes is also useful. Wang proposed a scheme to lengthen the lifetime of critical nodes near the sink of a network by moving certain nodes [11].

In this paper, we propose a novel adaptive fidelity algorithm called Hierarchical Geographic Adaptive Fidelity (HGAF) that gives a layered structure to the active node selection mechanism of GAF for further power reductions.

The remainder of this paper is organized as follows. Section 2 outlines GAF. The HGAF algorithm is presented in Section 3. In Section 4, we discuss the connectivity between nodes that work with GAF and HGAF when the nodes are arranged at random. In Section 5, we present the results of a simulation of GAF and HGAF. Section 6 concludes this paper.

2. Geographic Adaptive Fidelity (GAF)

GAF, the basis of HGAF, is an adaptive fidelity algorithm in which nodes working as cluster heads are selected in a distributed manner. GAF assumes that a large number of sensor nodes are placed in the observation area. The fewest nodes in the observation area are selected to transmit messages, while the other nodes sleep. In this way, GAF reduces the number of nodes needed to form a network and saves node battery power.

GAF divides the observation area into square areas and groups nodes according to their position. In each group, one active node is selected to work as the cluster head for routing packets between groups. Other nodes sleep to save their battery power. The selection of the active node in each group is done in a distributed manner by referring to the remaining battery power of each node.

2.1 Grid Layout in GAF

GAF assumes that all nodes have their own location information. Each node divides the whole observation area into square areas and groups nodes accordingly. Assume that the observation area is divided into squares with r units on a side, as shown in **Fig. 1**. We call each square a cell. Each node decides which cell it belongs to according to its position. One active node is selected in each cell. Thus, if we can enlarge the cell size, we can reduce the number of active nodes in the network and save even more battery power. However, in enlarging the cell size, the communication between active nodes in two adjacent cells must be guaranteed because active nodes work as cluster heads. Therefore, the distance between the two farthest nodes in any adjacent cell has to be smaller than the radio communication range. The maximum cell area S_{GAF} is constrained by the maximum radio communication range of sensor nodes R. The length of each cell r has to satisfy the following condition:

$$r^2 + (2r)^2 \leq R^2.$$

Thus,

$$r \leq \frac{R}{\sqrt{5}} \tag{1}$$

The maximum cell area is thus

$$S_{GAF} = (\max r)^2 = \frac{R^2}{5}. \tag{2}$$

2.2 State Transitions

In GAF, nodes are in one of three states: sleeping, discovery, or active. The

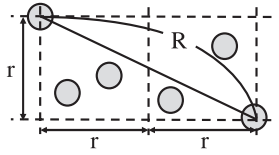


Fig. 1 Virtual grid in GAF.

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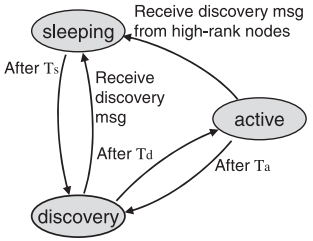


Fig. 2 State transitions in GAF.

state transition diagram is shown in **Fig. 2**. Nodes start out in the discovery state. One node in each group is selected as an active node, by referring to the residual battery power of nodes in the group. The active node in each group is changed dynamically as time passes. When a node is in the discovery state, it turns on its radio and broadcasts a discovery message to find other nodes within the same group. Each discovery message includes a node ID, group ID, estimated node active time, and the node state. Half of the estimated node active time is denoted by T_a. When a node enters the discovery state, it sets a timer which expires T_d seconds later. When the timer goes off, the node broadcasts a discovery message and becomes active. Then it sets a timeout value T_a that specifies the length of time in which it can stay active. After T_a, the node returns to the discovery state. While in the active state, the node periodically broadcasts its discovery message at intervals of T_d.

A node in discovery or active states can change to the sleeping state when it receives a discovery message.

- When a discovery node receives a discovery message, it goes into the sleeping state.
- When an active node receives a discovery message, the node compares its own expected lifetime with the one in the discovery message. If the former is longer than the latter, the node goes into the sleeping state.

A sleeping node wakes up after T_s seconds and goes back into the discovery state. T_s is calculated from the estimated node operation time of the current active node, which is written in the received discovery messages.

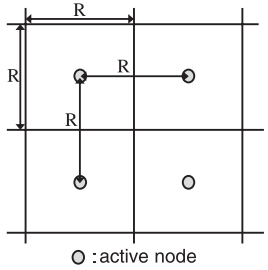


Fig. 3 Limiting the position of nodes.

3. Hierarchical Geographical Adaptive Fidelity (HGAF)

3.1 Basic Idea

Hierarchical Geographical Adaptive Fidelity (HGAF) saves much more battery power by enlarging the cell of GAF by adding a layered structure for selecting an active node in each cell.

As stated in the previous section, GAF saves battery power by enlarging the size of a cell. The connectivity between active nodes in two adjacent cells must be guaranteed because active nodes work as cluster heads to deliver packets between cells. Because of this limitation, GAF needs an active node in every area whose maximum size is $R^2/5$.

HGAF limits the position of an active node in a cell and synchronizes the position in each cell among all cells. Through this modification, the connectivity between active nodes in two adjacent cells can be guaranteed for a larger cell than in GAF.

If the relative positions of all active nodes to each cell are synchronized and the distance between them is constant as shown in **Fig. 3**, the distance between active nodes in two adjacent cells can be the same as the maximum communication range R. This makes it possible to enlarge the cell size to R^2 which is five times the maximum cell size of GAF. It means that the number of active nodes that HGAF requires is a fifth of what GAF requires. Thus, many nodes can save battery power while they are not active.

However, it is difficult to completely synchronize the relative position of an

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active node to the cell in which the node is located, because nodes are not placed at even intervals. Thus, we divide a cell into square areas and limit the location of an active node to one of these square areas.

3.2 Hierarchical Selection of Active Node

By selecting an active node from nodes in an active sub-cell of each cell and synchronizing the relative position of the selected sub-cell (active sub-cell) in each cell among all cells, we can roughly synchronize the positions of active nodes in each cell. All nodes in sub-cells other than active sub-cells stay asleep until the sub-cells become active. In each active sub-cell, an active node is chosen on the basis of the GAF algorithm.

3.3 Grid Layout in HGAF

In HGAF, as in GAF, communication between active nodes in two adjacent cells and between an active node and other nodes in the same cell must be guaranteed. Thus, the distance between the two farthest nodes in two adjacent cells (OP in **Fig. 4**) should be less than the radio communication range R.

We now describe the effect of decreasing the number of active nodes by using a hierarchical structure for selecting the active node. Let the number of sub-cells on one side of each cell be N. The number of sub-cells in a cell is N^2. We assume each cell is a square with D_N units on a side, and each sub-cell is a square with d_N units on a side, as shown in Fig. 4. To guarantee the connectivity between any nodes in adjacent cells of GAF, the distance between the two farthest nodes in two adjacent cells OP must not be larger than the radio communication range R.

Thus, OP has to satisfy the following condition:

$$(OP)^2 = (d_N)^2 + ((N+1)d_N)^2 \leq R^2$$

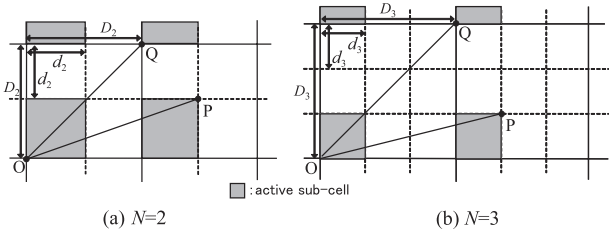
We can rewrite the equation as follows:

$$d_N \leq \frac{1}{\sqrt{(N+1)^2+1}} R \tag{3}$$

Let us use the length of the side of a cell $D_N = Nd_N$ to rewrite inequality (3) as follows:

$$D_N \leq \frac{N}{\sqrt{(N+1)^2+1}} R \tag{4}$$

Thus, the cell area S_N and sub-cell area s_N have to satisfy the following conditions:



(a) N=2 (b) N=3

Fig. 4 A cell divided into N^2 sub-cells.

$$s_N = (d_N)^2 \leq \frac{1}{(N+1)^2+1} R^2$$
$$S_N = (D_N)^2 \leq \frac{N^2}{(N+1)^2+1} R^2 \tag{5}$$

In HGAF, as in GAF, active nodes act as cluster heads of each cell (not sub-cell). Therefore, each active node must be guaranteed connectivity to all nodes in the same cell. The length of the diagonal line of a cell, e.g., in Fig. 4. OQ, must be less than the maximum communication range R. In Fig. 4, OQ has to be equal or less than R. Thus, the length of a side of a cell D_N has to satisfy:

$$\sqrt{2} D_N \leq R. \tag{6}$$

The following inequality is obtained by referring to inequalities (4) and (6):

$$\frac{\sqrt{2}N}{\sqrt{(N+1)^2+1}} \leq 1 \tag{7}$$

The only integers N that satisfy this condition are 1 and 2. Thus, when $N \geq 3$, the maximum cell area is limited by inequality (6) and we cannot enlarge the cell area by more than $R^2/2$.

3.4 Rotation of Active Sub-Cells

In HGAF, active sub-cells are periodically rotated for load balancing. Let T be the length of time each sub-cell is active. All cells use the same rotation schedule. Thus, all nodes have to know the rotation timing before the operation begins and synchronize their clocks. **Figure 5** shows the schedule of active sub-cells when

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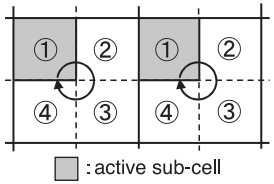


Fig. 5 Rotation of active sub-cells.

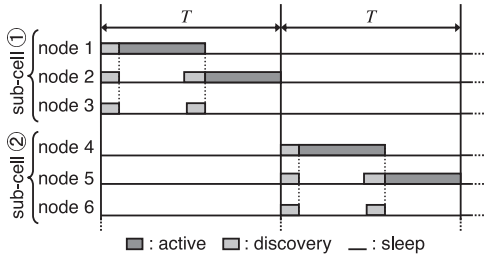


Fig. 6 Simple schedule in HGAF.

$N = 2$. Active sub-cells rotate every T seconds according to the circled numbers in Fig. 5. The circled numbers mean the sequence of active sub-cells rotation.

We use the simple sub-cell rotation shown in **Fig. 6**. When a sub-cell becomes active, all nodes in the new active sub-cell move to the discovery state and behave according to the same GAF algorithm in order to select a new active node in the sub-cell. T seconds after the sub-cell becomes active, all nodes in the sub-cell go into the sleeping state.

Positions measured by GPS and other positioning schemes and the local clocks of the nodes always include errors, and these errors may waste energy. If a node in a sleeping sub-cell has location information or local clock including errors, it might decide that it is in an active sub-cell and try to be an active node. In such a case, the connectivity between an active node in a sleeping sub-cell and an active node in the neighboring cell will not be guaranteed. This increases the number of packet losses and energy consumption. To minimize the effect of position and clock errors, the distance between a new active-sub cell that was selected after a periodic rotation of active sub-cells and the previous sub-cell should be small.

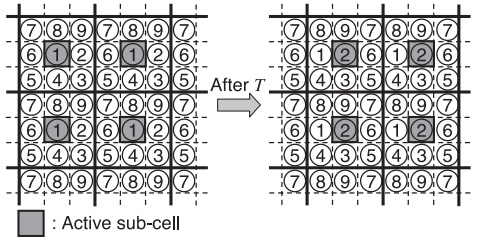


Fig. 7 Extended HGAF.

3.5 Extended HGAF (EHGAF)

As stated in Section 3.3, when N is larger than two, the maximum cell size of HGAF is limited by the distance between the active node and other nodes in the same cell. However, we can relax this restriction by moving the boundary of cells by moving the active sub-cells (see **Fig. 7**). We call this scheme Extended HGAF (EHGAF). In EHGAF, the cell boundary moves as an active sub-cell that is kept at the center of the cell. Through this modification, the maximum distance between an active node in a cell and other nodes in the same cell can be shorter than the original HGAF. Because the cell that a node belongs to depends on the boundary of the cell, all nodes should know their current cell ID as well as their sub-cell ID changed through rotation of the active sub-cell.

The connectivity between an active node and other nodes in a cell is guaranteed in EHGAF. Below, we explain the reason for this when N is an odd number and when N is an even number.

3.5.1 When N Is an Odd Number

When N is an odd number, there is a sub-cell including the center point of the cell (**Fig. 8**). In this case, OW is the maximum distance between the active node and other nodes in the same cell. OW has to be less than R because of the connectivity between the active node and other nodes in a cell. Thus, OW has to satisfy the following condition with d_N and D_N:

$$OW = OV + VW = \frac{\sqrt{2}}{2} d_N + \frac{\sqrt{2}}{2} D_N \leq R \tag{8}$$

Because N is an odd number, by replacing N with $N = 2n - 1$ $(n = 1, 2, 3 \cdots)$, OW has to satisfy the following conditions according to inequalities (3) and (4):

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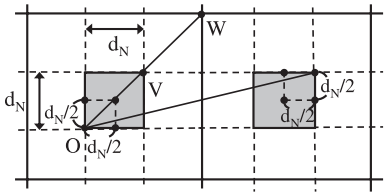


Fig. 8 Case in which N is an odd number.

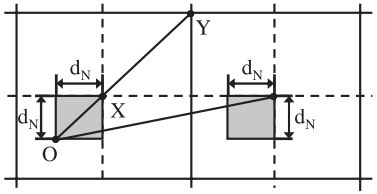


Fig. 9 Case in which N is an even number.

$$\frac{\sqrt{2}n}{\sqrt{4n^2+1}} \leq 1 \tag{9}$$

Because n is larger than zero, the condition is always satisfied.

3.5.2 When N Is an Even Number

When N is an even number, there are a number of sub-cells sharing the center point of the cell (**Fig. 9**). Let us assume that an arbitrary sub-cell lying next to the center point of the cell is active. In this case, OY is the maximum distance between an active node and other nodes in the same cell. OY has to satisfy the following condition:

$$OY = OX + XY = \sqrt{2}d_N + \frac{\sqrt{2}}{2}D_N \leq R \tag{10}$$

Replacing N with $2n$ ($n = 1, 2, 3 \cdots$), we can obtain the following condition for n:

$$\frac{\sqrt{2}(1+n)}{\sqrt{(2n+1)^2+1}} \leq 1 \tag{11}$$

Because n is larger than zero, this condition is always satisfied.

4. Analysis of Available Sub-Cells of HGAF

In HGAF, the sub-cell size decreases with increasing N. Therefore, the probability that nodes exist in a sub-cell decreases with increasing N. If there are no nodes in a sub-cell, connectivity between neighboring cells is not guaranteed. Thus, HGAF needs sufficient node density so that all nodes can communicate with a sink.

In this section, we assume that the maximum cell size of GAF or HGAF (when $N \geq 3$, we use EHGAF) is used. We analyze the ratio of sub-cells where at least one node exists and estimate the maximum data collection ratio of WSNs with HGAF.

First, we obtain the probability of nodes existing in a sub-cell. We suppose that the nodes are almost uniformly distributed throughout the observation field if they are seen from a macroscopic point of view. Let the number of nodes in a cell with the maximal cell size of GAF be B_1. The average of the number of nodes in each cell when each cell is divided into N^2 sub-cells, B_N, is calculated as follows:

$$B_N = B_1 \frac{S_N}{S_1} = B_1 \frac{5N^2}{(N+1)^2+1} \tag{12}$$

Assuming nodes in each cell are arranged at random, the probability that a certain node exists in a sub-cell can be expressed $1/N^2$. Let $P_0(N)$ denote the probability that no nodes exist in a sub-cell. Because the probability that a node does not exist in a sub-cell is denoted by $(1 - 1/N^2)$, $P_0(N)$ is expressed as a function of N and B_1 as follows:

$$P_0(N) = \left(1 - \frac{1}{N^2}\right)^{B_N} = \left(1 - \frac{1}{N^2}\right)^{5N^2 B_1/\left((N+1)^2+1\right)} \tag{13}$$

Figure 10 plots the $P_0(N)$ for various B_N and N. The case with $N = 1$ is equivalent to GAF. $P_0(N)$ decreases with a larger number of nodes. This is because HGAF limits the area where active nodes can exist by dividing a node into many sub-cells. Thus, HGAF needs a lot of nodes when N is large.

Secondly, we estimate the appropriate node density for N. We call a sub-cell where at least one node exists an *available sub-cell*. The probability that a sub-

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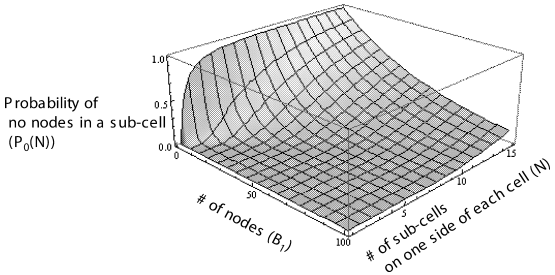


Fig. 10 Relation between N and the number of nodes.

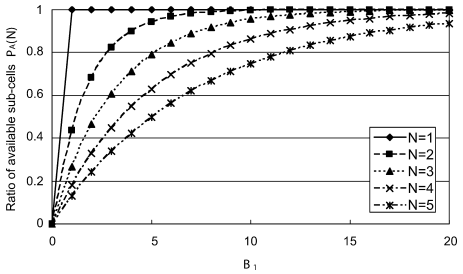


Fig. 11 Relation between B_1 and ratio of available sub-cells.

cell is an available sub-cell is $(1 - P_0(N))$. Let the ratio of available sub-cells in a cell divided into N^2 sub-cells be $P_A(N)$. $P_A(N)$ is expressed by using the expected value of the number of available sub-cells in a cell. Let the probability that there is m available sub-cells in a cell be $P_{A_m}(N)$. $P_{A_m}(N)$ is a function of N and $P_0(N)$:

$$P_{A_m}(N) = {}_{N^2}C_m \cdot (1 - P_0(N))^m \cdot P_0(N)^{(N^2-m)} \tag{14}$$

Thus, $P_A(N)$ is

$$P_A(N) = \sum_{k=1}^{N^2} \frac{k}{N^2} P_{A_k}(N) \tag{15}$$

$$= \sum_{k=1}^{N^2} \frac{k}{N^2} \cdot {}_{N^2}C_k \cdot (1 - P_0(N))^k \cdot P_0(N)^{(N^2-k)}. \tag{16}$$

Figure 11 plots $P_A(N)$ for various B_1 and N. Assuming all nodes sense data and send them to a sink node, because data obtained by nodes in each cell have to be forwarded to an active node in an active sub-cell in the cell, $P_A(N)$ gives the upper bound of the successful data delivery ratio. In order to obtain $P_A(N) \geq .8$ for $N = 2$, 3 and 4, B_1 has to be equal or greater than 3, 5, and 8 respectively.

5. Evaluation

We compared GAF, HGAF, and EHGAF in terms of the number of surviving nodes and packet delivery ratio by simulation using ns-2 network simulator [12]. We set the number of sub-cells on the side of each cell N to 2 (HGAF), 3 (EHGAF) and the rotation interval of the active sub-cell T to 1,500 s in HGAF. We assume that nodes do not have any time error, because the time error is much smaller than the rotation interval. The time error is often smaller than 100 ms [13),14)]. All simulation results represent an average of 20 simulation runs.

5.1 Arrangement of Simulation Field

The number of active nodes depends on the cell size, as described in Section 3. Therefore, the sizes of the simulation area and the cell size should be carefully chosen to ensure a fair comparison. We set the node communication range to 40 m. In this case, the maximum length of a GAF cell side is 17.89 m. The maximum cell-side lengths of HGAF (N=2) and EHGAF (N=3) were set to 25.30 m and 29.10 m, respectively. In order to use the maximum cell size when the boundary of the field is on the boundary of cells, the length of a simulation field should be the LCM of the length of the GAF and HGAF cell sides. However, such a field is very large. Therefore, we chose the cell size of GAF, HGAF (N=2), and EHGAF (N=3) to ensure a fair comparison.

The simulation field was a square, 250.44 m a side, as shown in **Fig. 12**. GAF, HGAF (N=2) and EHGAF (N=3) had 196, 100 and 81 cells in the field, respectively. The lengths of the cell sides were 17.89 m, 25.04 m and 27.82 m, respectively. Therefore, the ratios of the lengths to maximum cell sides of each configuration were respectively 100.0%, 99.0% and 95.6%. That is to say, we used 100.0%, 98.0% and 91.4% of the area of the maximum cell. The ratio of the cell area for HGAF to the maximum cell area was slightly smaller than the ratio for GAF. This condition is sufficient for a fair comparison of HGAF and

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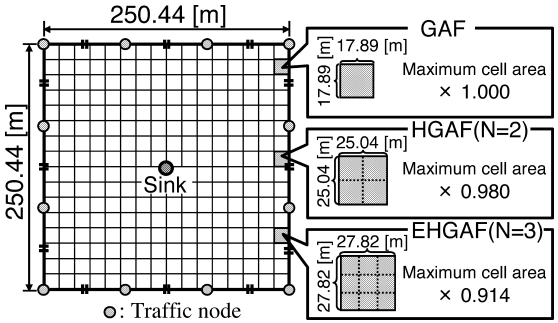


Fig. 12 Simulation field.

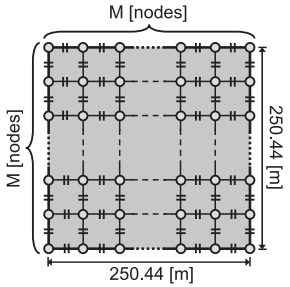


Fig. 13 Uniform placement of transit nodes.

GAF. The ratio of the number of cells in GAF and HGAF gives us the lifetimes of nodes: up to 195.9% ($25.04^2/17.89^2$) for HGAF (N=2) and EHGAF (N=3) and 241.8% ($27.82^2/17.89^2$) for GAF.

In our simulations, nodes are placed uniformly and randomly. Nodes are placed as shown in **Fig. 13** when nodes are placed uniformly.

5.2 Traffic Model

We used 12 traffic nodes as data source nodes, and we randomly or uniformly set 400, 800, and 1,200 transit nodes (Fig. 13). All traffic nodes sent an 80-byte packet to the sink node every 4 minutes. We used IEEE802.15.4 [15] for the MAC layer. The link bandwidth was 250 kbps. AODV [16] was used for packet routing. The transit nodes did not generate data; they only transferred data generated by the traffic nodes. We only used GAF, HGAF and EHGAF on the transit nodes.

5.3 Energy Model

We gave the sink node and traffic nodes an infinite supply of energy and gave each transit node 5 J. Our energy consumption model was based on MPR2400CA (Crossbow Technology) [17]. It assumes costs of 59.1 mW for transmitting, 52.2 mW for receiving, 0.06 mW for listening and 0.003 mW for sleeping. We neglected energy consumption other than wireless communications in our simulation because the transmit nodes did not have sensors and we assumed they were static and assigned their positions beforehand.

5.4 Positioning Error Model

We gave traffic nodes a static positioning error. Let the error radius of the positioning error Δ. Δ was uniformly distributed from 0 to 5, 10 and 15 m. The error direction was also uniformly distributed over $[0, 2\pi)$. Traffic nodes determine their behaviors according to their positions including the error instead of their real positions.

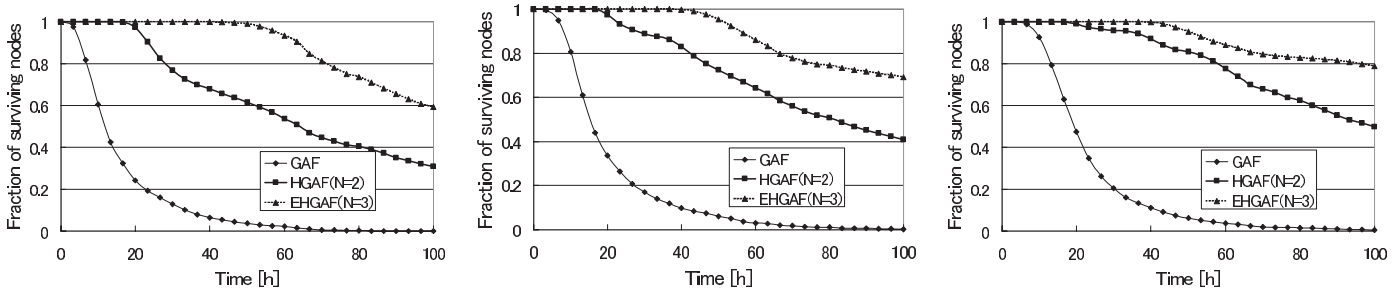
5.5 Comparison of the Fraction of Surviving Nodes

The percentages of surviving nodes over time with 400, 800, and 1,200 transit nodes are shown in **Fig. 14**. The more transit nodes we use, the longer the lifetime of nodes. The fraction of surviving nodes in HGAF and EHGAF is always higher than that in GAF. The ratio of the times until 20% of the nodes died (80% nodes survive) is about 400% for HGAF (N=2) and EHGAF (N=3) and 800% for GAF; these ratios are all more than the expected value presented in Section 5.1. The GAF algorithm has a large overhead for sending route discovery messages of AODV. On the other hand, only nodes in an active sub-cell transmitted the messages in the cases of HGAF and EHGAF. Nodes in sleeping sub-cells do not send discovery messages. Thus, HGAF and EHGAF saved power by decreasing the number of active nodes.

5.6 Data Delivery Ratio

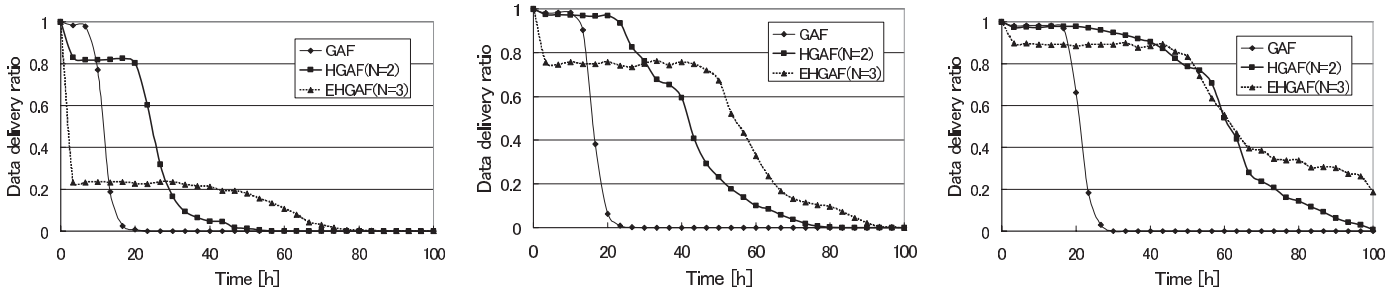
Even if the fraction of surviving nodes is large, if the data packets are not delivered to the sink, the power saving technique is not useful. We evaluated the data delivery ratio of GAF, HGAF and EHGAF. The data delivery ratios over time with 400, 800, and 1,200 transit nodes are shown in **Fig. 15**. HGAF and EHGAF's data delivery ratios are higher than GAF's in the case of 800 and 1,200 transit nodes. We define the network lifetime as the length of time that the data

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(a) 400 transit nodes (b) 800 transit nodes (c) 1,200 transit nodes

Fig. 14 Fraction of surviving nodes over time (Random placement, $\Delta = 0$ m).



(a) 400 transit nodes (b) 800 transit nodes (c) 1,200 transit nodes

Fig. 15 Data delivery ratio over time (Random placement, $\Delta = 0$ m).

delivery ratio is over 80%. In Fig. 15 (b), we can see that the network lifetime of HGAS is 200% of GAF. With much more high node density (Fig. 15 (c)), HGAF and EHGAF can achieve about 250% network lifetime compared with GAF.

However, when there are only 400 transit nodes, HGAF and EHGAF's data delivery ratios are lower than GAF's until about 3,200 s. There are fewer nodes in an HGAF and EHGAF sub-cell than in a GAF cell because HGAF selects only one active node in each sub-cell and its sub-cell size is smaller than GAF's. This means there is a high probability that an HGAF and EHGAF sub-cell will have no node when the number of nodes in the field is small. If there is no active node in a sub-cell, the transmission of packets sent from the cell and destined for the cell fails. Routing of other packets may also fail. These problems degrade HGAF's data delivery ratio. However, this problem can be resolved by placing nodes uniformly so that each sub-cell can have at least one node. **Figure 16** shows the data delivery ratios over time with 742 transit nodes when transit nodes are arranged uniformly. Though EHGAF (N=3) in Fig. 16 has a smaller number of nodes than in Fig. 15 (b) and Fig. 15 (c), it achieves a high data delivery ratio.

5.7 Effect of Node Density

In HGAF, a cell which has no active node can not forward packets. Thus, the performance of HGAF is worse than GAF when the node density is low because some sub-cells have no node.

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To find the lower bound of the number of nodes that HGAF saves more energy than GAF, we conducted simulations changing the number of nodes from 100 to 1,200. **Figure 17** shows the lifetime of the network formed by randomly placed transit nodes. When the number of nodes is less than 400, HGAF's network lifetime is very short because the node density is not enough for all sub-cells to contain at least one node. If there are more than 400 nodes, HGAF outperforms GAF. EHGAF needs many more nodes than HGAF to achieve longer network lifetime because EHGAF restricts the position of nodes to a small area to enlarge the size of cells. We can see that EHGAF ($N = 3$) outperforms HGAF ($N = 2$) when there are more than 1,150 nodes.

5.8 Effect of Estimation Error of Node Positions

The data delivery ratios over time with 800 transit nodes including positioning error in GAF, HGAF (N=2) and EHGAF (N=3) are shown in **Fig. 18**. We can see that GAF is hardly affected by positioning errors. However, the data delivery ratio of HGAF (N=2) and EHGAF (N=3) decreases with the increasing positioning errors. Moreover, this effect increases with increasing N, because HGAF (N=2) and EHGAF (N=3) limits the position of active nodes with increasing N. As a result, the distance between active nodes becomes larger when N is large. If the cell size is the largest for given R and N, the minimum distance between active nodes is $\frac{N-1}{\sqrt{(N+1)^2+1}}$. For $N = 2$ and 3, the distance is about 0.316 and

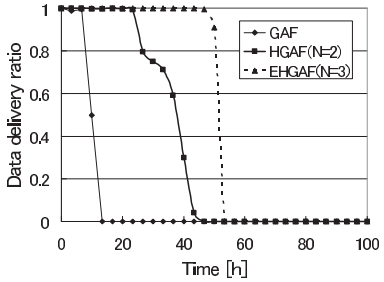


Fig. 16 Data delivery ratio over time (742 transit nodes placed at even intervals, $\Delta = 0$ m).

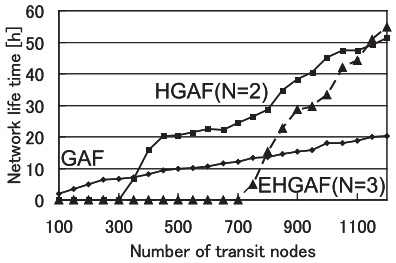
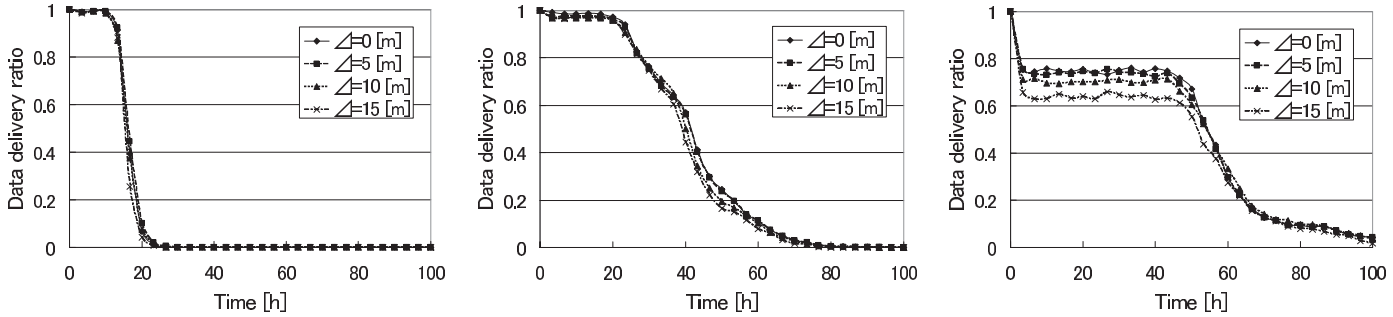


Fig. 17 Network lifetime with various node density.



(a) GAF (b) HGAF ($N = 2$) (c) HGAF ($N = 3$)

Fig. 18 Effect of positioning error (800 transit nodes, Random placement).

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0.485 while the distance of GAF is 0. Thus, if N is large, the distance between the real position of active nodes easily becomes larger than R. This results in disconnectivity between active nodes.

6. Conclusion

We proposed an adaptive fidelity algorithm called Hierarchical Geographic Adaptive Fidelity (HGAF) that gives a layered structure to the active node selection mechanism of GAF. We evaluated HGAF on ns-2 network simulator. The simulation results revealed that HGAF outperforms GAF in terms of energy efficiency and packet delivery ratio. In particular, when the node density is high and each cell is divided into four sub-cells, the network lifetime with HGAF is about 200% as long as GAF. In this study, we assumed the energy consumption of all nodes was uniform regardless of the communication range and communication error other than collisions did not occur. However, the actual energy consumption and packet error rate depend on the communication distance. Because HGAF's average communication distance between active nodes is longer than GAF's, the results may differ from the case we studied. Investigation of the effect of communication distance remains for the future work.

We used square cells because GAF used them. However, we expect that HGAF with hexagonal cells outperforms GAF with square cells in terms of packet delivery ratio, because the connectivity between active nodes in adjacent cells in six directions can be guaranteed by using hexagonal cells. On the other hand, it is difficult to enlarge the cell when we divide a hexagonal cell into sub-cells equally because the hexagonal cell has to use a salient sub-cell. Nevertheless, we have an idea to enlarge the cell size according to the number of divisions. In the near future, we will develop HGAF with hexagonal cells.

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Editor's Recommendation

This paper proposed a novel protocol called HGAF (Hierarchical Geographic Adaptive Fidelity) in wireless sensor networks. HGAF is an extended version of the previously proposed GAF, and it achieves power saving using location information. The authors show through simulations that HGAF outperforms GAF in a dense network in terms of packet delivery ratio and that HGAF prolongs the lifetime of networks. The achievement of the paper gives a significant contribution to the further development of the future mobile computing.

(Chairman of SIGMBL Takashi Watanabe)



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