A Routing Protocol with High Node Exchangeability for Sustainable Sensor Networks

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SUMMARY Recently, wireless sensor networks have been seen as a key technology for a ubiquitous computing society. In sensor networks, many network technologies have been developed, whose main concern is reduction of power consumption of sensor nodes. Moreover, these conventional approaches assume that a node in a sensor network operate in a finite quantity and initial battery of a node. However, if we use the sensor network in the natural environment, it means that the batteries of nodes must be exchanged to long term operation. From a viewpoint of the environmental sustainability it is also necessary for sensor nodes to be easily collected and replaced. This paper proposes a routing protocol for sensor networks with high node exchangeability in order to realize the continuous long-term operations of sensor networks. In the proposed routing protocol, power consumption of nodes is partially biased and the region is rotated in order to exchange a set of nodes easily. We evaluate the proposed routing protocol using DSR and a routing protocol where all nodes try to consume the battery equally. We use evaluation metrics biased toward transmitting data, the battery residue of nodes at the exchange time, the transition of operating nodes. The results show that the difference of the battery residue between the largest and the smallest nodes is 88% and node exchangeability improves by restricting the geographical area of exchanging nodes.

key words: sensor network, routing protocol, sustainability

1. Introduction

Recently, wireless sensor networks have been seen as a key technology for realizing a ubiquitous computing society [1]. In order to acquire various kinds of environmental information, many small sensor nodes can be located or embedded in various fields. For instance, applications of sensor networks for civil engineering, intelligent transportation, and space technology have been developed. Generally, battery constraint is limited for sensor nodes because of hardware simplicity. To improve power consumption performance, many network technologies such as MAC (Medium Access Control), and routing schemes have been developed. Some typical schemes include Sensor-MAC (S-MAC) [2] and Low-Energy Adaptive Clustering Hierarchy (LEACH) [3], and approaches based on routing protocols such as Directed diffusion [4] and Geography-informed Energy Conservation for Ad Hoc Routing (GAP) [5], and the approach based on the arrangement of nodes [6].

These conventional approaches aim to reduce the power consumption of each node, and all nodes in the whole network consume battery almost equally. However, if we use the sensor network in the natural environment, it should be operating for longer at least than lifetime of a battery. It means that the batteries of nodes must be exchanged to avoid a negative impact on the environment for long term operation. For instance, sensor nodes may be embedded in a field. In this case, since the battery of all nodes becomes empty sooner or later, nodes must be exchanged for new ones. Therefore, sensor nodes should be exchanged partially for continuous use in a field because it is difficult to exchange all nodes at once. However, it is easy to imagine that all nodes in a network could be drained at the same time in the conventional approaches. Moreover, in the conventional approach, it is necessary to stop the whole network for all the nodes to be replaced. For long-term continuous operation of the sensor network, novel concept about high node exchangeability should be developed.

In this paper, we propose a routing protocol to improve node exchangeability. In the proposed protocol, nodes in a sensor network send to the sink node via nodes in the specific area. And nodes in there are emptied earlier than other nodes so as to easily specify and exchange their nodes. We assume two types of the operations in the conventional approaches. They are networks whose nodes are exchanged by each node, and all nodes are exchanged. We evaluate the proposed routing protocol and compared it with the conventional approaches by means of computer simulations. As a result, the effectiveness of the proposed routing protocol is discussed.

2. The Concept of the Sustainable Sensor Networks

2.1 Sustainable Sensor Networks

In this paper, we use “sustainable” as “environmentally sustainable.” More exactly, it means “able to be continued without a significant negative impact on the environment or its inhabitants.” As to sensor networks, when sensor nodes are scattered or placed in the natural environment, those nodes should be collected to avoid the negative impact after their batteries die out and then replaced by new ones with fully charged batteries for a long term operation to achieve the network function.

Figure 1 shows the difference between the conventional
and proposed approaches in both concept and application. The conventional approach is effective in cases where the battery life is sufficient for the required operation time of the sensor networks. In contrast, the proposed approach is designed using node exchange. Therefore, the proposed approach is effective in cases in which the required operation time is much longer than the battery life continuously. We conclude the following definition of the node exchangeability. First, nodes are emptied and biased into a specific geographical area. Second, the time at which nodes are emptied is specified at a specific time. These make it possible to exchange nodes partially without affecting the whole sensor network and to exchange nodes easily. We show some approaches to realize node exchangeability as defined in a subsequent.

2.2 The Sustainable Applications for the Sustainable Sensor Networks

In a sensor network, the following items must be taken into consideration for the exchange to take place:

- The amount of power remaining in the node’s battery
- Deterioration and other problems the node may face in a harsh environment
- Node exchange that can be achieved if a new device is developed

We illustrate with the following example of an application for sustainable sensor networks. There is an application which locates nodes in a bridge and monitors the condition of the bridge [7]. Figure 2 shows the basic concept for the exchange nodes located in a bridge. We assume that a large number of nodes are embedded in the bridge. The sensor nodes monitor the aging condition of the bridge or the traffic on the bridge, etc. In the conventional approaches, when the nodes should be exchanged, the target of the exchange is all nodes simultaneously. Additionally, the function of the sensor network and bridge are stopped during the node exchange. During the node exchange, no car runs through the bridge as shown on the left of Fig. 2. In contrast, in the proposed approach, since the nodes can be exchanged partially, the bridge can still operate. Therefore, cars can run through the bridge as shown on the right Fig. 2. Thus, the proposed scheme does not significantly hinder the function of the bridge.

3. The Proposed Routing Protocol to Localize Energy Consumption

At first, the service area is divided into plural zones. One of the zones is defined as the initial main relaying zone. Sensing data are intentionally routed to the sink node via the main relaying zone. Therefore, power consumption of the nodes in the main relaying zone becomes larger than that of those in the other zones. In addition, compared with conventional approaches, we can reduce the control packet for acquiring the battery residue of nodes, and the control packet for the necessity of the exchange. The routing scheme aims at continuous long-term operation. The algorithm is showed in the pseudo code in Appendix A. The basic procedure of the proposed routing is shown as follows:

1. Dividing nodes into plural groups by geographical areas
2. The sink chooses a zone to be the initial main relaying zone
3. All nodes send data through the main relay zone, and nodes in the main relay zone are emptied faster
4. All nodes in the main relay zone are replaced by new ones
5. The sink determines the next main relay zone which has the least amount of battery residue of the zones
6. Go to 3

Each node is configured with a zone ID which is based on the geographical coordinates at its initial location. Each node has a routing table. The routing table includes node IDs, zone IDs, and the number of hops between the sink, neighboring zones, itself and all neighbor nodes. A sample routing table is shown in Fig. 3.

In the proposed routing scheme, three kinds of control packets are defined for constructing the routing table. One is the hop count packet. Another is the hello packet. The
other is the relay hop count packet.

At first, the hop count packet includes the hop count from the sink. The sink initiates and floods a hop count packet by setting the hop count to 1 for the whole network. When a node receives the hop count packet, the node records the value of the hop count in its own routing table. In addition, the node increments the hop count and forwards the hop count packet.

Secondly, the hello packet includes node ID, zone ID, and the number of hops from the sink. Each node sends the hello packet to neighboring nodes to set their own node ID, zone ID, and number of hops from the sink. When a node receives the hello packet, the node records each value of the hello packet into its own routing table. Thus, the node knows the information of its neighbor nodes.

Finally, the relay hop count packet includes the hop count from a node in neighboring zone. If the routing table of a node has nodes with different zone ID, the node floods the relay hop count packet by setting the relay hop count to 1 only for nodes with the same zone ID. When a node receives the relay hop count packet, the node records the value of the relay hop count into the relay hop count of the sender in its own routing table. In addition, the node increments the relay hop count and records the value of the relay hop count into the relay hop count of itself in its own routing table. In addition, the node forwards the relay hop count packet.

In Fig. 3, if the main relay zone is zone 3, node 5 searches zone ID in its own table to send data. Node 5 finds node 6 in zone 3 and sends data to node 6. If the main relay zone is zone 1, node 5 searches zone IDs in its own table to send data. Because node 5 does not know nodes in zone 1, node 5 searches same zone IDs in its own table. Node 5 compares its own hop count to zone 1 with that of nodes in the same zone and finds node 4, which has a hop count to zone 1 that is 1 smaller than that of its own. Node 5 sends data to node 4. Node 4 relays the data by the same processes.

In addition, if battery residue of a node is below a specific value, the node sends data to the sink with an empty flag setting. Because the sink receives the data with the empty flag setting and knows the battery residue of all nodes, the sink determines the exchange time.

Figure 4 shows an example of the operation under a rectangular environment. We assume that the sensor network is divided into three zones of X1, X2 and X3 geographically, and each of their nodes in each zone consumes their own battery equally. Nodes in each zone have 3 units of batteries. Nodes observe environment information every 1 unit of time, and send data related to it. Nodes consume 1 unit of battery for data sending or relaying. At time \( t = 0 \), zone X3 is specified as the initial main relay zone. All nodes send data to the sink via zone X3 from time \( t_0 \) to \( t_1 \). The battery residue of the node in zone X1 becomes 2 units of battery because the node sends the data and consumes 1 unit of battery for each 1 unit of time. The battery residue of the node in zone X2 becomes 1 unit of battery because the node sends not only data but also relays the data of the nodes in zone X1 and consumes 2 units of battery. The battery residue of the node in zone X3 becomes empty because the node not only sends data but also relays both kinds of data from the nodes in zone X1 and zone X2. The proposed protocol repeats these procedures in which the battery residue of the node in the main relay zone becomes empty early and replaces nodes.

Table 1 shows the difference of the characteristic between the proposed protocol and the conventional approaches. In the case that nodes in a network are exchanged by one by one, nodes in sensor network try to reduce the battery consumption and consume their battery equally. Thus, the power consumption is efficient. Moreover, it is possible to specify exchange time because we can estimate ex-
change time by the number of nodes and its sending rate. However, it is difficult to specify exchange nodes more exactly than the proposal because some of nodes in the sensor network consume their battery equally. Because nodes are exchanged one by one, a network can operate continuously, while a number of exchange time increases. It also takes much time to collect and replace nodes one by one, which means low exchangeability.

In the case that all nodes in a network are exchanged at the same time, nodes in sensor network try to reduce the battery consumption and consume their battery equally. Thus, the power consumption is efficient. Moreover, it is possible to specify exchange time because it is possible to estimate exchange time by the number of nodes and their sending data. It is possible to specify exchange nodes because all nodes in sensor network are exchanged at the same time. The small number of exchange time is required. However, it is necessary to stop the whole network for all the nodes to be replaced. So, the sensor network operates intermittently.

In the proposed protocol, sensing data are intentionally routed to the sink node via the main relay zone. Nodes in the main relay zone are emptied earlier than other nodes. So, it is possible to specify exchange nodes. Moreover, it is possible to calculate exchange time by Eq. (1) in the Sect. 4.1. So, it is possible to specify exchange time. The sensor network operates continuously because exchange nodes are biased into the specific area. However, the power consumption is inefficient and exchange times are required increase because nodes in the main relay zone must send many data.

Therefore, in the proposed protocol, it is possible to exchange nodes easily and operate a sensor network in long-term continuously.

4. Performance Evaluation

In this section, we evaluate the proposed routing. We evaluate the following metrics: the battery residue of each zone, the distribution of nodes which require the exchange in the exchange time, the exchange cycle of the main relay zone, the rate of the data traffic of nodes, the total power consumption of the whole network per unit time, and the ease of the exchange.

4.1 Basic Evaluations

Here, we evaluate the performance of the proposed routing for a relatively simple network model. In Fig. 5, the network model we use for performance evaluation is shown. The service area is divided into three zones of X1, X2 and X3. We assume these nodes consume the battery equally when the proposed protocol operates ideally. We assume the initial main relay zone is zone X3. All nodes send data to the sink via the main relay zone. Each node has 27 units of battery at the beginning, and consumes 1 unit battery consumption per a sending or a relaying.

When a node in each zone observes sensing data, the data for the zone number of partitions aggregates to the main relay zone. If a node consumes the battery equally, the exchange cycle of the main relay zone is the value which divides the least battery residue by the number of partitions at the previous exchange time of the main relay zone. Figure 6 shows the exchange cycle obtained by computer calculation. It repeats ten exchanges as one cycle like the following turn.

 zone X3, X2, X1, X2, X3, X1, X2, X3, X2, X1. Figure 6 shows that the exchange interval is not simple.

We define the exchange time as \( t_i \), the number of zones as \( n \), and the battery residue in each zone as X1, X2 and X3. \( j \) is the value which a conditional equation does not exceed \( i \). In fact, \( j \) is the number of times which its zone becomes a main relay zone and is exchanged. \( t_i \) is calculated by the value which the total battery residue of each main relay zone is divided by the number of zones. For example, we assume that an initial battery of each zone is 9 and a number of zones are 3. When \( i \) is 1, \( j \) of X1 and X2 is 0 and \( j \) of X3 is 1. \( t_i \) is the value that the battery residue of nodes in X3 is divided by a number of zone. Therefore, \( t_i \) is 3. The following expression shows the main relay zone and its exchange time.

\[
  t_i = \frac{1}{3} \left( \sum_{i>0} \frac{X1_i}{(i+2)/3} + \sum_{i>0} \frac{X2_i}{(i+2)/3} + \sum_{i>0} \frac{X3_i}{(i+2)/3} \right) \quad (i = 0, 1, 2, \ldots)
\]  

In principle, if we exchange nodes at the time according to Eq. (1), the battery can be used without wasting completely. Therefore, the proposed routing protocol can simplify the system operation and management because the exchanging time is computed in advance.
4.2 Advanced Evaluations

In a real installment, collisions in MAC layer should be considered. Here, we discuss the protocol considering MAC collision and compare it with other routing protocols. We assume that the protocol is CSMA/CA in the MAC layer. We evaluate the performance in a more realistic environment. Table 2 shows the simulation parameters. A unit time is a second. These parameters are based on the standard of ZigBee. We define the threshold for an exchange because we need to consider the time required for an exchange and prevent the network from being fragmented into several parts in which nodes can not reach the sink. We define the threshold of an exchange as one hundredth of the capacity of the battery, a value just prior to when the battery becomes empty. We assume that the generation and sending of data follows the Poisson process in 1 unit time intervals. The initial main relay zone is Zone X3. Figure 7 shows the evaluation environment, which sets 36 nodes in a grid arrangement, and sets nodes in 10 meter intervals.

The comparative protocol is DSR [8] and Energy Efficient Routing (EER). We define EER for this evaluation. In EER, each node maintains a local table. The local table includes node ID, battery residue and the number of hops from the sink. Each node sends data to a node with the biggest battery residue and the smallest number of hops from the sink in the local table. Therefore, nodes in a whole network consume batteries equally. We divide each zone into X1, X2 and X3. Each of these 3 zones is then divided into 3 sub-zones as shown in Fig. 7. We assume that a sensor network is divided into three zones basically either in three-dimensional or in flat two-dimensional space. When the average battery residue in the sub-zone becomes less than that of the threshold of the battery exchange, we define this time as the target of the exchange. In the proposed routing, we exchange all sub-zones in zones X1, X2 and X3 in which the sub-zone surpasses the threshold of the battery exchange. In DSR, nodes which are exchanged in the sub-zone need to be exchanged. In EER, nodes in a whole network consume a battery equally. Therefore, when nodes can not send data to the sink, we consider this the end of the sensor network lifetime and exchange all nodes in the sensor network. The operation of the proposed routing is as follows:

1. The node sends data with information concerning battery residue
2. The sink acquires the battery residue of all nodes
3. The sink determines the exchange cycle and the main relay zone

4.2.1 The Battery of Nodes at the Exchange Time

First, we evaluate the battery of nodes at the first exchange time. Figure 8 shows the battery residue distribution and the distribution of the number of nodes with more than the threshold for node exchange at the first exchange time. The value in brackets is the number of nodes with more than the threshold for node exchange. The first exchange time is 41.0 [unit time] in the proposed protocol, 90.0 [unit time] in DSR and 99.2 [unit time] in EER. The value of the battery residue is the rate when its initial value is 100%. This results in an average battery residue for each zone of 86% (X1), and 68% (X2), and 29% (X3) in the proposed protocol. It is shown that the average battery residue of each zone is different. Therefore, we can see that the batteries of the nodes in the main relay zone are emptied earlier than those in the other zones, and thus we can specify the area that needs to be exchanged. This results in an average battery residue of each zone of 42% (X1), and 31% (X2), and 46% (X3) in DSR. This results in an average battery residue for each zone of 32% (X1), and 32% (X2), and 33% (X3) in EER. The difference of the battery residue between the largest

**Table 2** The evaluation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The transmission rate</td>
<td>250 [kbps]</td>
</tr>
<tr>
<td>The communication range</td>
<td>15 [m]</td>
</tr>
<tr>
<td>The detection range</td>
<td>20 [m]</td>
</tr>
<tr>
<td>The capture threshold</td>
<td>10 [dB]</td>
</tr>
<tr>
<td>Data size</td>
<td>800 [bit]</td>
</tr>
<tr>
<td>The sending current</td>
<td>12 [mA]</td>
</tr>
<tr>
<td>The receiving current</td>
<td>1.8 [mA]</td>
</tr>
<tr>
<td>The initial battery</td>
<td>20 [µAh]</td>
</tr>
<tr>
<td>The threshold of an exchange</td>
<td>0.2 [µAh]</td>
</tr>
</tbody>
</table>

**Fig. 8** The difference between the battery residue and the distribution of the number of nodes surpasses the threshold of the exchange at the first exchange time.
and the smallest zones in the subdivision Zone is 88% in the proposed protocol, 72% in DSR and 69% in EER. It is shown that EER consumes the battery equally over the entire network. Exchanging nodes is effective when the battery residue becomes less than the threshold for the exchange in the proposed protocol. However, these results of the average battery residue in zone X3 are 29% at the time of exchange.

The proposed protocol includes nodes which need to be exchanged into the main relay zone. Nodes which are far from the sink still have enough battery. DSR scatters nodes that need to be exchanged across the whole network. EER empties nodes near the sink. In EER, it is inevitable that nodes near the sink are empty earlier because they relay a lot of data. Therefore, we observe that EER can specify nodes that need to be exchanged, too.

In addition, until this exchange time, the proposed protocol consumes 271.0 [µA]. DSR consumes 427 [µA]. EER consumes 482 [µA]. So, the power consumption per unit time is 6.61 [µA/unit time] in the proposed protocol, 4.74 [µA/unit time] in DSR and 4.85 [µA/unit time] in EER. The proposed protocol consumes 1.39 times more power compared with DSR and 1.36 times more power compared with EER. This is because the number of hops for relaying in the proposed protocol is greater than that for DSR and EER.

4.2.2 The Amount of the Data Traffic of Nodes

Figure 9 shows the amount of the data traffic of nodes. The left side of Fig. 9 is the value which is calculated by the equation (Appendix B). The amount of the data traffic is derived by the appendix. The right side of Fig. 9 is the value of the simulation result in this section. We assume that R is 25 m, and T_{Arrival} is 1 unit time) because the Poisson process in 1 unit time intervals. In addition, V_{x,y} is approximated by a rectangular zone such as Fig. A-2. Note that the value of the data traffic is normalized by the least data traffic. The theoretical figure is calculated by substituting evaluation parameters. In the Lattice Geometry of this evaluation, the area of node of n hops is divided in a direction parallel to the sink, and is ideally the same. We assume that the area of node of n hops, S_n, is same.

The simulation result is almost similar to the theoretical figures. In the simulation result, the data traffic of nodes in the main relay zone is larger than that of the theoretical. The reason is due to data collision in MAC layer. In particular, because nodes of the center sub-zone are surrounded by many nodes of neighbor zones, the data traffic of nodes of the center sub-zone is the least for nodes in zone X2. The same is true of a sub-zone in the main relay zone.

4.2.3 The Transition of the Number of the Operating Nodes

Secondly, we evaluate the performance of long-term continuous operation of the sensor network. We define the time required for an exchange. We assume that a sensor network system which operates for one year needs about 20 days. Therefore, we determined that the sensor network system needs a period of one twentieth of its lifetime for the exchange. The previous evaluation (Fig. 8) shows that a lifetime of the sensor network in EER is about 100 [unit time]. EER exchanges all nodes at the exchange time. Therefore, in this section, we define the time required for an exchange.

Fig. 9 The rate of the data traffic of nodes (the proposed protocol).

<table>
<thead>
<tr>
<th>Sink</th>
<th>1.0</th>
<th>2.0</th>
<th>9.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.2</td>
<td>2.6</td>
<td>11.0</td>
</tr>
<tr>
<td>1.0</td>
<td>2.0</td>
<td>6.0</td>
<td>6.9</td>
</tr>
<tr>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Theoretical figure Simulation result

Fig. 10 The transition of the number of the operating nodes.
as 5 [unit time] in EER. We define this as 2 [unit time] in the proposed protocol because the proposed protocol exchanges nodes in each zone. We define this as 1 [unit time] in DSR because DSR exchanges nodes in each sub-zone. Nodes which are exchanged can not transmit data during a period of the exchange. Nodes which are rearranged construct a routing table again and begin to transmit data.

Figure 10 shows the transition of the number of the operating nodes in 500 [unit time]. Zone exchange occurs 16 times in the proposed protocol. In the proposal protocol, two-third of the nodes operate constantly. In DSR, 77% of nodes operate on an average. The number of operational nodes changes randomly. There are 4 instances of all nodes exchange simultaneously in EER. Because all nodes are exchanged at the same time, the whole network stops temporarily.

The proposed protocol can easily specify nodes to be exchanged because the battery of the nodes in the main relay zone is emptied earlier than those in the other zone. In addition, two-third of nodes can operate constantly. Therefore, the proposed protocol is useful for the continuous long-term operation of sensor networks. The proposed protocol also features a lot of exchanges and high power consumption per unit of time.

5. Discussion on Partial Interruption of the Network

The proposed routing to localize energy consumption has high exchangeability in a sense that it enables a partial group of nodes to be replaced at once. However, during the exchange the sensing data from the partial network must cease to flow, while the rest of the network does not. In some applications even the partial interruption is critical and unacceptable. For this problem, an additional mechanism can be simply applied. The mechanism is based on scheduling of active/sleep mode of each node in MAC layer. The procedure is as the followings.

1. At each location to be observed a pair of nodes is installed
2. One node of the pair is initially to collect data
3. This type of node is referred to as a Longer-active Group (LG) node
4. The other is initially almost to be asleep
5. This type of node is referred to as a Shorter-active Group (SG) node
6. LG nodes consume more energy than SG nodes

Figure 11 shows an example of active/sleep schedules of nodes in the two groups. A node belonging to LG has a long active period as shown in Fig. 11. On the contrary, if a node belongs to SG, it has a short active period.

LG nodes observe the environment, while SG nodes almost sleep and wake periodically in active to monitor the battery residue of their peer LG nodes. After a LG node drains its batteries, the LG node and the SG node switch their role. That is, the former LG nodes are replaced to new ones or fully charged, those new ones are initialized to be SG nodes and the former SG nodes become LG nodes to collect sensing data. Therefore, the entire network can operate without break. Note that some other studies also proposed the idea to be applied but for the difference objective. In Coverage-Preserving Node Scheduling [9], nodes in a sensor network construct cluster groups. And a cluster head in a cluster group control the length of the active period of nodes in the group. In Two-Tiered Scheduling Algorithm (TTS) [10], nodes are divided three groups; one group keeping connectivity to the sink, another group observing the environment, and the third group keeping asleep. Although their objectives are to improve the performance by localizing traffic and keeping connectivity to the sink, as a solution of the partial interrupt two groups such as LG and SG are sufficient.

6. Conclusion

In this paper, we have proposed an approach for sensor networks with high node exchangeability in order to realize the continuous long-term operations without a significant negative impact on the natural environment. We have focused on routing protocol biases toward the power consumption of specific larger nodes, and evaluation it in an ideal condition. We have showed that it is possible to derive the data traffic of each node. We have showed that the zone-to-zone battery residue is different, and it is possible to derive the exchange area and the exchange cycle. Additionally, we have evaluated the proposed routing under realistic condition. The difference of the the battery residue between the largest and the smallest nodes is 88%, and the target of exchange nodes are specified in the main relay zone. Because the exchange nodes and cycles can be specified, we showed that the proposed routing improves node exchangeability more than DSR and EER. The proposed routing can operate a sensor network continuously for much longer-term.

In the future, we will consider nodes which do not surpass the threshold of the exchange in the exchange zone. Moreover, we should improve the total consumption of power per unit of time in the whole network.
References


Appendix

A: The Proposed Algorithm for n Zones

01: Sensor network area = (0−x, 0−y)  
02: Number of all nodes = n, Node = (a, b)  
03: Number of zone = z  
04: i = a / z  
05: switch  
06: case ‘i’ : into group i  
07: the main relay zone = initial zone  
08: while (endless) {  
09:  while (main relay zone has battery) {  
10:     if (not main relay zone)  
11:        send data to main relay zone  
12:    else  
13:        send data to sink  
14: }  
15: exchange main relay zone  
16: main relay zone = the least battery zone  
17: }  

B: Analysis of the Power Consumption of Each Node

In the proposed routing protocol, sensing data are intentionally routed to the sink node via the main relaying zone. Therefore, a node near the sink consumes more power than that far from the sink due to data relay. In this appendix, we analyze the power consumption of each node theoretically.

Figure A-1 shows the analytical model. We consider that all nodes are in a coordinate with (s, t), where s is the number of hops from the sink, t is the number of hops from the main relay zone. We analyze the total transmitted data of nodes at (s, t), defined as M_s,t. In the proposed routing, at first, a node sends data to a node in the main relay zone. Next, the node in the main relay zone relays the data to the sink. Therefore, as shown in Fig. A-1, a node at (s, t) sends three kinds of data. One is the generated data in its subzone s, defined as V_s. Another is the relay data from nodes in subzone s + 1, defined as V_s+1. The other is the relay data from nodes in subzone s + 1, defined as V_s+1.

We introduce the total transmitted data of nodes of n hops from the sink, defined as M_n. M_n is derived as follows:

\[ M_n = \begin{cases} M_{n+1}\times p_{n+1,1} + V_n & (0<n<H_{\text{max}}) \\ V_n & (n = H_{\text{max}}) \end{cases} \quad (A-1) \]

where \( p_{n+1,1} \) is the probability that nodes of \( n + 1 \) hops from the sink can send a data to nodes of \( n \) hops from the sink successfully. \( V_n \) is the amount of data generated by nodes of \( n \) hops. \( H_{\text{max}} \) is the maximum number of hops from the sink. M_n is derived recursively. We derive V_s first. Next, we derive p_{n+1,1}.

We assume that nodes are arranged in the area of \( R \) in the radius as shown in Fig. A-2. A_i is the set of nodes of \( n \) hops and \( i \in A_k, j \in A_{k+1} \). The area of node of \( n \) hops is \( S_n \), and \( S_{n+1} \) is approximated as a rectangle. The whole sensor network generates the total amount of data, V. The data generated in nodes of \( n \) hops, \( V_n \), is derived as follows:

\[ V_n = V \times \frac{S_n}{\pi R^2} = V \times \frac{R^2}{2 \pi R^2} = \frac{V}{2 \pi} \quad (A-2) \]

As shown in the above, \( V_n \) is independent in the number of hops from the sink, and is a constant.

We derive \( p_{n+1,1} \). \( N_n \) is a number of nodes in \( n \) hop from the sink. Since a node has \( N_{\text{neighbor}} \) neighbor nodes, the total relay data from neighbor nodes of \( n \) hops, \( m_n \), is,
where \( H_{\text{max}} \) is the maximum number of hops from the main relay zone, and \( H_{\text{max, s}} \) is the maximum number of hops from the sink, respectively. In case of \( t = H_{\text{max}} \), nodes send only own generated data. In case of \( 0 < t < H_{\text{max, s}} \), \( s = H_{\text{max, s}} \), nodes send relay data from the nodes of \( t + 1 \) hops from the main relay zone in addition to the own generated data. In case of \( 0 < s < H_{\text{max, s}} \), nodes send relay data from the nodes of \( t + 1 \) hops from the main relay zone and relay data from the nodes of \( s + 1 \) hops from the sink in addition to own generated data.

\[
m_n = M_n \times \frac{N_{\text{neighbor}}}{N_n}. \tag{A.3}
\]

\( T_{\text{Arrival}} \) (sec) is the average interval of the arrival of neighbors’ data in MAC layer. The data frame size is \( Z_{\text{data}} \) (bits). The total data frame generated by neighbor nodes per \( T_{\text{Arrival}} \) in a node \( n \) hops from the sink, \( f_{i,j} \), is

\[
f_{i,j} = \frac{m_n}{T_{\text{Arrival}} Z_{\text{data}}}. \tag{A.4}
\]

The transmission rate is \( B \) (bps). The time period which is required to send a data frame, \( \tau \), is the value which is \( Z_{\text{data}} \) divided by \( B \). We assume that the data generation of a node follows the Poisson process in \( \tau \). When data which generate \( f_{i,j} \) times in \( \tau \) averagely generate \( F \) times, the probability is

\[
p_F(f_{i,j}) = \frac{(\tau f_{i,j})^F e^{-\tau f_{i,j}}}{F!}, \tag{A.5}
\]

When \( i \) can receive data from \( j \), \( j \) sends data and the other nodes do not send data, i.e., \( F = 1 \). The probability, \( \alpha \), which only \( j \) sends data is

\[
\alpha = \frac{p_1(f_{i,j})}{N_{\text{neighbor}}}. \tag{A.6}
\]

The probability, \( \beta \), of \( i \) sending data, is the value of the time required for sending data divided by \( T_{\text{Arrival}} \) (sec).

\[
\beta = \frac{m_n}{N_{\text{neighbor}} B T_{\text{Arrival}}}. \tag{A.7}
\]

Therefore, \( p_{n+1,n} \) is

\[
p_{n+1,n} = \frac{\alpha}{\beta} \quad (0 < n < H_{\text{max}} + 1) \tag{A.8}
\]

By using \( V_r \) derived by Eq. (A.2) and \( p_{n+1,n} \) derived by Eqs. (A.2) to (A.8), we can obtain \( M_n \) of Eq. (A.1). After obtaining \( M_n \), we derive \( M_{k,t} \), which is defined as the total data traffic of nodes of \( s \) hops from the sink and \( t \) hops from the main relay zone.

\[
M_{k,t} = \begin{cases} 
V_r & (t = H_{\text{max}}) \\
V_r & (0 < t < H_{\text{max}}, s = H_{\text{max}}) \\
M_{s,t+1} \times p_{t+1,t} + V_r & (0 < s < H_{\text{max}}) 
\end{cases} \tag{A.9}
\]

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