Routing Protocol of Sustainable Sensor Networks with High Exchangeability of Nodes

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Abstract

In this paper, in order to realize the consecutive long-term operations of sensor networks, we propose a novel sustainable sensor network routing protocol considering easy node exchangeability. In the proposed routing protocol, in order to exchange nodes easily, power consumption of nodes is biased intentionally. We focus on a routing protocol for the sustainable sensor networks. In the proposed routing protocol, the power consumption of nodes in a specific zone becomes larger than that in other zones. Battery of nodes in the specific zone is emptied earlier. As restricting the geographical area of the node exchange, node exchangeability improves. We evaluate the proposed routing protocol by means of computer simulations to show the effectiveness of the proposed routing protocol.

1. Introduction

Recently, wireless sensor networks are becoming a key technology for realizing an ubiquitous computing society [1]. In order to acquire various kinds of environmental information, many small sensor nodes can be located or embedded in devices 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 protocol such as Directed diffusion[4] and Geography-informed Energy Conservation for Ad Hoc Routing (GAF)[5], and the approach based on the arrangement of nodes[7].

These conventional approaches aim to reduce power consumption of each node, and all nodes in the whole network consume battery equally. These conventional approaches are effective in short-term or temporal operation of sensor networks. However, it is not consider the case that sensor network operates consecutively for much longer-term than the battery lifetime. For instance, sensor nodes are embedded in a building. In this case, since the battery of all nodes becomes empty sooner or later, node exchange to new one is necessary. Sensor nodes should be exchanged partially for consecutive use of the building because it is difficult to exchange all nodes at once. However, it is easy to imagine that all nodes in a network are emptied at the same time in the conventional approaches. Moreover, in the conventional approach, it is necessary to stop the whole network, and all nodes are replaced.

For long-term consecutive operation of the sensor network, novel concept about node exchangeability should be considered.

In this paper, in order to realize the consecutive long-term operations of sensor networks, we propose novel sustainable sensor network framework considering easy node exchangeability. In the proposed framework, to exchange nodes easily power consumption of nodes is biased intentionally. We consider various biasing power consumption approaches. Among them, in particular, we focus on proposing a routing protocol for the sustainable sensor network framework. In the proposed routing protocol, the power consumption of nodes in specific zone becomes larger than that in other zones intentionally. Nodes in a specific zone are emptied earlier. As restricting the geographical area of the node exchange, node exchangeability improves. We evaluate the proposed routing protocol by means of computer simulations. As a result, the effectiveness of the proposed routing protocol is shown.

2. The concept of the proposed sustainable sensor networks

Sensor nodes have the limitation of the battery, and the battery is depleted soon or later. The conventional studies do not consider a case that the required consecutive operation of the sensor network is much longer than the battery lifetime of the node. Therefore, in the conventional approach, it is necessary to stop the whole network, and all nodes are replaced. Otherwise, a node is exchanged in each time the node is emptied. If sensor nodes are embedded, the reactive node exchange is difficult. If nodes are not embedded, the cost of node exchange becomes large. Thus, the conventional approaches cannot realize consecutive long-term operation. We propose novel sustainable sensor network framework with easy node exchangeability for realizing consecutive long-term sensor network operation. Fig. 1 shows the difference of the concept and the application between the conventional and proposed approaches. The conventional approach aims to reduce battery consumption. The conventional approach is effective in case that the battery life is sufficient for the required operation time of the sensor networks. On the contrast, the proposed approach is designed considering node exchange. Therefore, the proposed approach is effective in case that the required operation time is much longer.
than the battery life.

We conclude the following definition of the node exchangeability.

First, nodes are emptied are biased into a specific geographical area. Second, the time which nodes are emptied is pinpointed into a specific time. These are possible to exchange nodes partially without affecting the whole sensor network and to exchange nodes easily. We show some approaches to realize the defined node exchangeability in subsequent section.

2.1. The sustainable applications for the proposed sustainable sensor networks

In a sensor network, the case which needs the exchange has the following items:
- The emptiness of the node’s battery
- The deterioration and problems of the node in a harsh environment
- The exchange of nodes by the development of the new device

We illustrate the following example application for sustainable sensor networks

There is an application which locates nodes in a bridge and monitors the condition of the bridge [8]. Fig. 2 shows the basic concept for the exchange nodes located in a bridge. We consider 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.

3. Routing to localize energy consumption

We propose a routing scheme to localize energy consumption. In the proposed routing scheme, 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 consumptions of the nodes in the main relaying zone become larger than those in the other zones. In addition, we can reduce the control packet for the battery residue of nodes, and the redundant processing for transmitting the necessity of the exchange. The routing scheme aims at continuous long-term operation. The basic procedure of the proposed routing is shown as follows:

1. Dividing nodes into plural groups by geographical areas
2. The sink decides a zone as the initial main relay zone.
3. All nodes send data through the main relay zone, and nodes in the main relay zone are emptied earlier
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 a zone ID which is based on geographical coordinates at the initial location. Each node has a routing table. The routing table includes node IDs, zone IDs, number of hops from the sink and neighbor zones of oneself and all neighbor nodes. The routing table is shown in Fig. 5.

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.

First, the hop count packet includes the hop count from the sink. The sink initiates and floods a hop count packet with setting hop count 1 to the whole network. When a node receives the hop count packet, the node records the value of hop count into own routing table. In addition, the node increments the hop count and forwards the hop count packet.

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

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

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

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

Fig. 6 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 t0 to t1. The battery residue of the node in zone X1 becomes 2 units of batteries 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 batteries. 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 of the nodes in zone X1 and zone X2. The proposal protocol repeats these procedures in which the battery residue of the node in the main relay zone becomes empty early and replaces nodes.

4. Performance Evaluation

In this section, we evaluate the proposal routing by computer simulation. 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 total power consumption of the whole network per unit time, and the ease of the exchange.

4.1. Basic evaluations

We evaluate the performance of the proposed routing by means of a simple network model. In Fig. 7, 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 to 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 batteries at the beginning, and consumes 1 battery when sending and 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.
The exchange cycle. It repeats ten exchanges as one cycle. Fig. 8 shows the exchange zone. Fig. 8 shows that the exchange cycle. It repeats ten data distribution between nodes. The left side of Fig. 9 shows the battery residue in zone X1 and zone X2.

We define the exchange time to be \( t_i \), and the battery residue in each zone to be X1, X2 and X3. The following expression shows the main relay zone and its exchange time.

\[
 t_i = \frac{1}{n} \sum_{\alpha \in \{0, 1, 2, \ldots, n-1\}} X_1^{(\alpha \in \{0, 1, 2, \ldots, n-1\})} + \sum_{\beta \in \{0, 1, 2, \ldots, n-1\}} X_2^{(\beta \in \{0, 1, 2, \ldots, n-1\})} + \sum_{\gamma \in \{0, 1, 2, \ldots, n-1\}} X_3^{(\gamma \in \{0, 1, 2, \ldots, n-1\})}
\]

In principle, if we exchange nodes at the time of expression 1, we can use the battery can be used without wasting it completely. Therefore, we consider that the proposed routing protocol can simplify the system operation and management because the exchanging time is computed in advance.

### 4.2. Advanced evaluations

We assume that the protocol is CSMA/CA in the MAC layer. We evaluate the performance in a more realistic environment. Table 1 shows the simulation parameters. These parameters are based on the standard of ZigBee. When the battery of the nodes is emptied, nodes cannot send data to the sink, and the network stops operating. Time is thus required for node exchange. Therefore, we define a threshold for node exchange, which is one tenth of the capacity of the battery. We consider it as the value just prior to when the battery becomes empty. We assume that the sending data generation follows the Poisson process in 1 unit of time intervals. The initial main relay zone is Zone X3.

In this section, we assume that data communications are sent to the sink by multi-hopping through not only the adjacent zone but also the same zone. We can adopt the sensor network to the immense area by multi hopping data distribution between nodes. The left side of Fig. 9 shows the evaluation environment, which sets 36 nodes in a grid arrangement, and sets nodes in 10 meters intervals.

The comparative protocol is DSR [9]. We divide each zone into X1, X2 and X3. Each of these 3 zones is then divided into 3 sub-zones. These 9 sub-zones are referred to as sub-zone A to I as shown on right side of Fig. 9. We define the threshold of an exchange because we need to consider the time required for an exchange and preventing a network from being fragmented into several parts in which nodes can not reach the sink. When the average battery residue in the sub-zone becomes less than that of the threshold of the battery exchange, we define the time to be the target of the exchange. 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. The operation of the proposed routing is as follows:

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

Fig. 10 shows the battery residue distribution at the exchange time. The value of the battery residue is the rate when its initial value is 100%. This results in the average battery residue of each zone as 90% (X1), and 72% (X2), and 43% (X3) in the proposed protocol. It is shown that the average battery residue of each zone is different. Therefore, we consider that the battery of the nodes in the main relay zone are empted earlier than those in the other zone, thus we can pinpoint the area that needs to be exchanged. This results in the average battery residue of each zone as 36% (X1), and 42% (X2), and 56% (X3) in DSR. The difference of the battery residue between the largest and the smallest zones in the Subdivision Zone is

<table>
<thead>
<tr>
<th>Evaluation parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The transmission speed</td>
<td>250[kbps]</td>
</tr>
<tr>
<td>The communication range</td>
<td>10[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>1[µAh]</td>
</tr>
<tr>
<td>The threshold of an exchange</td>
<td>0.1[µAh]</td>
</tr>
</tbody>
</table>

![Graph showing the battery residue distribution at the exchange time](image)
shows the cases which adopt DSR. In DSR, sensing data are exchanged, and the exchange itself is problematic. The proposed protocol includes nodes which need to be exchanged into the main relay zone. DSR scatters nodes needed to be exchanged into the whole network. Therefore, we consider that the exchange in the proposed protocol is easier than that of DSR, because the proposed protocol can pinpoint nodes needed to be exchanged easily.

Fig. 11 shows the distribution of the number of nodes which surpass the threshold for node exchange at the exchange time. The proposed protocol considers nodes which need to be exchanged are scattered in the whole network. Therefore, we consider that the exchange in the proposed protocol is easier than that of DSR, because the proposed protocol can pinpoint nodes needed to be exchanged easily.

![Figure 11](image1)

**Figure 11:** The distribution of the number of nodes in Subdivision zone G (DSR)

Fig. 12 shows the transition of the battery residue of 4 nodes which are configured in each Subdivision Zone of G in right side of Fig. 9. Fig. 12-(a) shows the cases which adopt the proposed protocol. Fig. 12-(b) shows the cases which adopt DSR. In DSR, sensing data is routed via the shortest path from a node to a sink, and the nodes which need to be exchanged are scattered in the whole network. Therefore, we consider it to be difficult to pinpoint the location of nodes which need to be exchanged, and the exchange itself is problematic.

![Figure 12-(a)](image2)

**Figure 12-(a):** The transition of the battery residue of the nodes in Subdivision zone G (the proposal protocol)

![Figure 12-(b)](image3)

**Figure 12-(b):** The transition of the battery residue of the nodes in Subdivision zone G (DSR)

The number of hops for relaying in the proposed protocol is larger than that for DSR. Therefore, the total power consumption is 2.8 units in the proposed protocol, and is 2.33 units in DSR and the proposed protocol consumes 1.2 times more power compared with DSR.

In this evaluation, the initial battery is 0.5 [µA-unit time]. When the generation interval of each node is the Poisson process in 2 [unit time], the first exchange time of the proposal protocol is 1.95×10^{-3} [unit time] as shown in Fig. 12-(a).

5. Conclusion

In this study, we propose approaches considering easy node exchangeability to realize the consecutive long-term operations of sensor networks. We focus on the routing protocol biases power consumption of specific nodes larger than that of other nodes, and evaluation it in an ideal condition. We show that the zone-to-zone battery residue is different, and it is possible to derive the exchange area and the exchange cycle. Additionally, we evaluate the proposed routing under a realistic condition, and show that the target of exchange nodes is localized into a specific area and the proposed routing improves the node exchangeability easier than that for DSR.

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

References


