Proposal of Simple Route Reconstruction Method Using Sequence Number in AODV for Prolonging Node Lifetime

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Abstract Ad hoc on-demand distance vector (AODV) is an often used routing protocol in multihop communication. In AODV, there is a tendency for the first established route to be repeatedly used. This causes a problem that the remaining battery levels become uneven between the nodes used in the communication route and the other nodes. In this paper, we propose a simple route reconstruction method to ease the problem. The proposed method makes use of the sequence number that is used in the conventional AODV. We conduct a fundamental investigation into the lifetime of the first-dead node using a network simulator. The result shows that the proposed method with multiple thresholds can prolong the lifetime of the first-dead node by 11%. This means that the proposed method can contribute toward easing the problem of uneven battery consumption among the nodes.

Keywords: multihop communication, AODV, sequence number, lifetime of the first-dead node

1. Introduction

Mobile terminals are widely used in daily life. In wireless communication networks such as cellular phones, mobile terminals usually communicate via base stations. In such a case, if the base station becomes unusable, for example, due to a natural disaster, it becomes impossible for the mobile terminals to communicate with each other. As a method to avoid this situation, ad hoc communication in which mobile terminals communicate without base stations has been developed. The range of ad hoc communication is limited to the communication distance that the transmitted signal from the mobile terminal can reach directly. To enhance the communication range, multihop communication using a relay scheme has also been developed [1], [2]. In multihop communication, the mobile terminal becomes a node and forms a network by using wireless links. When a node must communicate with another node that is outside the communication distance, message packets are conveyed via some nodes on a multihop-relay basis. Then, the communication route is determined by a routing protocol. In the case of using mobile terminals, ad hoc on-demand distance vector (AODV) is an often used routing protocol because it has good adaptability to the node mobility. In AODV, there is a tendency for the first established route to be repeatedly used. This means that only the batteries of the nodes along that route are significantly consumed. This causes a problem that the remaining battery levels become uneven between the nodes composing that route and the other nodes. While a node works as a relay node at other times, it can sometimes be a source node. A relay node cannot be a new source node if its remaining battery is low because it cannot easily start to send data. Thus, it is desirable to prolong the lifetime of nodes when we use AODV. Some methods have been proposed to prolong the node lifetime. Jing and Lee [3] proposed a method to stop using the relay node when its remaining battery falls below the threshold level. Ikeda et al. [4] and Bhatsangave and Chirchi [5] proposed methods in which a node whose remaining battery becomes less than the threshold level does not participate in route construction. Saito et al. [6] proposed a method to construct a route avoiding nodes with a low battery level. In these methods, it is necessary to notify all nodes of the threshold level or the battery level of each node. Moreover, either the threshold level or the battery level should also be described in the control packet. This means that the size of the control packet increases and the route construction process becomes more complicated. In addition, it may be difficult to notify all nodes of these values under the condition that the area size and the number of nodes are uncertain. In the present paper, we propose a simple route reconstruction method to ease the problem that the remaining battery levels become uneven among the nodes [7]. The proposed method focuses on the sequence number that is used in the conventional AODV. We simulate the proposed method in a simple network and evaluate it from the viewpoint of the lifetime of the first-dead node in the network.
2. AODV

2.1 Process of route construction

Figure 1 shows an example of a node arrangement and its link topology, which we use to explain the route construction process of AODV [8]. In Fig.1, S, R0, R1, R2, and D denote the nodes of the source, relay 0, relay 1, relay 2, and the destination, respectively. Each node holds a sequence number (SN) to be used to construct a communication route. Now, let us suppose that S must communicate with D, but it knows no communication route to D. Then, S broadcasts a route request message (RREQ) to the adjacent nodes, which are R0 and R1 in Fig.1. The RREQ has the IP address of the destination (D) and an SN. The SN in the RREQ is the same as the SN held by the source (S). If R0 receives the RREQ, it compares its holding SN with the SN in the RREQ. If the SN in the RREQ is larger than the one held by R0, R0 updates its own SN to the SN in the received RREQ and rebroadcasts the RREQ to the adjacent nodes (Fig.2). If not, R0 discards the received RREQ. R1 and R2 perform in the same way as R0. When D receives the relayed RREQ, D sends a route reply message (RREP) to S (Fig.3). Then, the RREP is relayed to S by unicasting through the relay nodes that relayed the RREQ. When S receives the RREP, a route from S to D is established.

2.2 Process of route reconstruction

Let us suppose that the route between R0 and D is broken after the route shown in Fig.3 is established. Then, R0 sends a route error message (RERR) (Fig.4). When S receives the RERR, S recognizes that the current route is broken. Thus, S sends a new RREQ to construct a new route (Fig.5). Then, S increases its SN by one. At the same time, the SN in the new RREQ is set to the SN held by S. After that, the route reconstruction is performed in the same way as in Sect. 2.1.
2.3 Remaining battery level

To confirm the uneven distribution of the remaining battery, we perform AODV using a simulator and investigate the battery usage rate of the nodes. We use ns-3 [9], [10], [11] for the simulator. We distribute 10 nodes randomly in an area. The 10 nodes have the same initial battery level and some of them can work as relay nodes. We check the remaining battery level of the other nodes when any one of the 10 nodes has run out of its battery, that is, when the first-dead node appears. Figure 6 shows the result of one of the trials of the simulation. The horizontal axis represents the ranking of the nodes when we arrange the remaining battery levels of the nodes in ascending order. The vertical axis represents the ratio of the remaining battery to the initial value of the battery. The red line shows the result for static nodes and the black one shows the result for mobile nodes. Regarding the static nodes, the remaining battery level is divided into two states, one with nearly 0% and the other with nearly 100%, with a certain node number as the boundary. We observed a similar trend in other trials. For the mobile nodes, different trends were observed for each trial. A similar result to the case of static nodes was sometimes observed, and at other times there were roughly three states as shown by the black line in Fig.6. In all cases, the battery consumption became uneven among the nodes.

Fig. 6 Remaining battery level in AODV

3. Proposed Method

In the proposed method, we give relay nodes a threshold level of the remaining battery. Let us suppose that the route using R0 was constructed as shown in Fig.3. When the remaining battery of R0 falls below the threshold level, we make R0 send an RERR (Fig.7). After that, we set the SN of R0 to a large value. This is a different feature from the

Fig. 7 Proposed method (No.1)

Fig. 8 Proposed method (No.2)

Fig. 9 Proposed method (No.3)

Fig. 10 Proposed method (No.4)
conventional AODV. In the figure, we set it at 10 for example. When S receives the RERR, it increases its SN by one and broadcasts a new RREQ to the adjacent nodes (Fig.8). When R0 and R1 receive the new RREQ, they compare their SNs with the SN in the RREQ. Since the SN held by R0 is larger than the SN in the RREQ, R0 discards the received RREQ. In contrast, the SN held by R1 is smaller than the SN in the RREQ. Thus, R1 updates its SN to the SN in the received RREQ and rebroadcasts the RREQ to the adjacent nodes (Fig.9). R2 behaves in the same way as R1, and the new RREQ reaches D via R1 and R2. When D receives the RREQ, it sends an RREP to S via R1 and R2 (Fig.10). In this way, a new route is reconstructed that does not include R0 with a low remaining battery level. We summarize the different features of the proposed method from the conventional AODV as follows:

- Relay nodes have a threshold level of the remaining battery.
- When the remaining battery of the relay node falls below the threshold level, the node sends an RERR.
- The relay node sets its SN to a large value after sending the RERR. Hence, the SN of the relay node becomes different from that of S.

In the proposed method, it is unnecessary to notify all nodes of the threshold level each node has. Hence, we can use the same control packet as that in the conventional AODV.

4. Simulation Results

To analyze the proposed method, we conduct simulations using ns-3 [9]. For the investigation of fundamental characteristics, we use a simple network as shown in Fig.11. Since there are only two candidates of the relay node, R0 and R1, the proposed method uses them alternately every time route reconstruction occurs. For example, let us suppose that the first established route is S–R0–D. If route reconstruction occurs, the second established route becomes S–R1–D in most cases. Moreover, if another route reconstruction occurs, the new route becomes S–R0–D again. Table 1 shows the simulation parameters. The transmission current and the reception current are determined referring to [3], [11], [12]. We assume that S and D do not consume their batteries. Note that the node consumes its battery even if it is not included in the communication route, although its battery consumption is less than that when it is included in the communication route.

### 4.1 Node lifetime when using a single threshold

As the first step, we investigate the case in which we set a single threshold. Figure 12 shows the lifetime of the first-dead node when the threshold level \( \theta \) changes from 0 to 0.5. In Fig.12, the left vertical axis represents the lifetime of the first-dead node, the right vertical axis represents its improvement rate compared with the conventional AODV, and the horizontal axis represents the threshold level \( \theta \) expressed as a percentage. \( \theta \) of zero represents the performance of the conventional AODV. From the figure, when using the proposed method, the lifetime of the first-dead node depends on the threshold level. Moreover, the lifetime of the first-dead node is prolonged compared with that in the conventional AODV. When \( \theta \) is high, the remaining battery of the relay node soon

![Fig. 11 Network model in simulation](image)

![Fig. 12 Lifetime of the first-dead node (single threshold)](image)
falls below the threshold level. Thus, route reconstruction occurs early. However, the remaining battery of the relay node in the second established route also soon falls below the threshold level and route reconstruction occurs again. Hence, the first established route is used a lot. On the other hand, when $\theta$ is low, the relay node in the first established route is used a lot before the first route reconstruction occurs. Thus, the node in the first established route runs out of its battery before the battery of the node in the second established route is fully used. From the above, there is an optimum threshold level. From the figure, the maximum lifetime of the first-dead node is 1281.06 s, an improvement on that of the conventional AODV of 6.3% for $\theta = 0.25$ (25%). This figure shows the effectiveness of the proposed method.

Figure 13 shows the transition of the remaining battery level of R0 and R1 when $\theta = 0.25$. Although either R0 or R1 is randomly selected as the relay node in each simulation trial, we assume that R0 is always selected in the first established route to simplify the following discussion. The vertical axis represents the remaining battery level and the horizontal axis represents the simulation time. The red line shows the remaining battery level of R0, which is selected in the first established route, and the black line shows that of R1, which is used in the second established route. The dotted lines show the performance of the conventional AODV. Once a simulation trial starts, R0 first rapidly consumes its battery. When its battery level reaches $\theta$, route reconstruction occurs and the battery consumption of R1 becomes rapid. Owing to the setup of the simulator, a simulation trial terminates when the remaining battery level of the relay node becomes about 10%. From this figure, we can again confirm that the proposed method prolongs the node lifetime compared with that of the conventional AODV. Regarding the difference between the final battery levels of R0 and R1, we find that the difference obtained by the proposed method is smaller than that obtained by the conventional AODV. If we can fully use both R0 and R1, the difference in the final battery level between R0 and R1 will be small, and then the lifetime of the first-dead node will be prolonged. To realize this situation, we investigate the case in which we use multiple thresholds in Sect. 4.2.

In Fig. 13, we find that the gradient of line A is the same as that of line C. Similarly, that of line B is the same as that of line D. In addition, they are almost the same as those of the lines of the conventional AODV. However, it is difficult to analytically calculate these gradients because the energy consumption process is complicated. Thus, we calculated the gradients from the graph lines of the conventional AODV and found that those of lines A and B are $a_0 = -0.07474$ %/s and $a_1 = -0.05286$ %/s, respectively. When $y$ and $t$ denote the coordinates in the vertical and horizontal directions, the equations of lines A and B are expressed by $y = a_0 t + 100$ and $y = a_1 t + 100$, respectively. Let $t_1$ denote $t$ when $y = \theta$ on line A, and let $y_1$ denote $y$ when $t_1$ is substituted into the equations for lines B and C. Then, the equations of lines C and D are $y - y_1 = a_0 (t - t_1)$ and $y - y_1 = a_1 (t - t_1)$, respectively.

If the remaining battery level of R0 becomes 10% when line C reaches $\theta$, then the lifetime of the first-dead node becomes the maximum. Under this condition, the following equations are obtained:

\[
\begin{align*}
\theta &= a_0 t_1 + 100 \\
y_1 &= a_1 t_1 + 100 \\
\theta - y_1 &= a_0 (t_2 - t_1) \\
10 - \theta &= a_1 (t_2 - t_1)
\end{align*}
\]

where $t_2$ denotes $t$ when line C reaches $\theta$, and $\theta$ is represented as a percentage. From the above simultaneous equations, we obtain the optimum $\theta$ that maximizes the lifetime of the first-dead node as follows:

\[
\begin{align*}
\theta &= \frac{10 + 100a_0 - 100a_1^2}{1 + a_0 - a_1^2} \\
&= 25.44
\end{align*}
\]

where $\alpha = a_1/a_0$. We find that this value almost matches the result of the simulation in Fig. 12.

### 4.2 Node lifetime when using multiple thresholds

There are many ways to set multiple thresholds. In this paper, we consider the following simple method. We set the $k$th threshold level $\theta_k$ using the following expression:

\[
\theta_k = \theta_1^k
\]

where each threshold value is expressed as a decimal fraction, $\theta_1$ is the initial threshold level, and $k$ is an integer.
assume $\theta_k \geq 0.1$. Figure 14 shows the lifetime of the first-dead node when we use multiple thresholds. We change $\theta_1$ from 0.4 to 0.9. From the figure, we find that the lifetime of the first-dead node increases as $\theta_1$ increases from 0.4, taking the maximum value when $\theta_1 = 0.7$, for which we achieve 11% improvement. If we begin with $\theta_1 = 0.4$, the second threshold is $\theta_2 = 0.16$. Thus, we can use only two thresholds to control the route reconstruction. On the other hand, if we begin with $\theta_1 = 0.7$, we have six thresholds: the subsequent thresholds are $\theta_2 = 0.49, \theta_3 = 0.34, \cdots$, and $\theta_6 = 0.11$. In this case, route reconstruction occurs more frequently, which is why the first-dead node lifetime is prolonged. However, the improvement rate is decreased when we begin with $\theta_1 = 0.9$ instead of $\theta_1 = 0.7$.

Figures 15 and 16 show the transition of the remaining battery level when the initial threshold levels are 0.7 and 0.9, respectively. We again assume that R0 is always selected in the first established route. In both figures, the red line shows the remaining battery level of R0 that is selected in the first established route. R0 is also used in the $(2n-1)$th established route, where $n$ is an integer. Also, the black line shows that of R1, and it is also used in the $2n$th established route. In both figures, the difference between the final battery levels of R0 and R1 is small compared with that in Fig.13. This means that we can fully use R1 as the relay node as well as R0. Therefore, we can conclude that the proposed method with multiple thresholds contributes to prolonging the relay-node lifetime. Comparing Figs.15 and 16, there are many threshold levels in Fig.16. Once the route reconstruction process starts, not only S and D but also R0 and R1 have to send some control packets in the network. This process also consumes their batteries, but data packets are not conveyed during the process. Thus, frequent route reconstructions cause high battery consumption and reduce the node lifetime. That is why the improvement rate for $\theta_1 = 0.9$ is less than that for $\theta_1 = 0.7$ in Fig.14.

In this section, we verified the effectiveness of multiple thresholds in a simple network. The result suggests that there is a possibility of prolonging the lifetime of the first-dead node even in complicated networks. However, the threshold levels and the updating procedure used in this study will require reconsideration in the case of complicated networks. Moreover, although we increased the SN of the relay node by 3 for each route reconstruction, we will also need to reconsider the increment value. For complicated networks, it is important to consider how many nodes exist around each node to set the threshold levels and the increment value appropriately.
Thus, it will be necessary for the proposed method to incorporate a function to determine the number of surrounding nodes, for example, by observing the received packets carefully. If this function is used in the proposed method, each node will be able to change its threshold level and the increment value adaptively by itself, and the route reconstruction method presented in this paper will probably be effective for prolonging the node lifetime even in complicated networks.

4.3 Throughput performance

Here we show the throughput performance when we use the proposed method. As shown in Table 1, the data packet size is 512 bytes, the transmission rate is 1 Mbps, and the packet transmission interval is 1 s. In this investigation we define the throughput \( \eta \) as follows:

\[
\eta = \frac{\text{Average number of packets received by D}}{\text{Average lifetime of the first-dead node}}
\]

(8)

Since the packet transmission interval is 1 s, the number of transmitted packets is the same as the simulation time expressed in seconds. Moreover, the denominator of Eq. (8) corresponds to the simulation time. For example, in Fig.13, since the lifetime of the first-dead node is 1276 s, the simulation time is also 1276 s. Table 2 shows the average number of received packets and the throughput \( \eta \) when we set a single threshold, where \( \theta = 0, 0.2, 0.25, \) and 0.5. Although we were concerned about degradation of the throughput caused by route reconstruction, it can be seen from the table that the throughput does not actually decrease in the single-threshold case. By careful analysis of the simulation, we found that it takes about 0.5 s for a new route to be established after the route reconstruction starts. Since the packet transmission interval is set to 1.0 s and we use only one threshold, it is considered that the process of route reconstruction has a negligible effect on the throughput. Table 3 shows the average number of received packets and \( \eta \) when we set multiple thresholds, where \( \theta_1 = 0.4, 0.7, \) and 0.9. As can be seen in the table, as \( \theta_1 \) increases, the throughput decreases very slightly. As mentioned above, the number of threshold levels increases as \( \theta_1 \) increases. Thus, many route reconstructions occur when \( \theta_1 \) takes a large value. This increases the proportion of the route-construction time within the simulation time. As a result, the ratio of the time for data-packet transmission to the lifetime of the first-dead node decreases, and the throughput is also reduced. The number of packets received by D increases as the lifetime of the first-dead node increases. Thus, although the throughput is slightly degraded, the proposed method contributes to increasing the number of received data packets.

5. Conclusion

AODV is an often used routing protocol in multihop communication. When we use AODV, there is a tendency for the first established route to be repeatedly used. This causes a problem that the remaining battery levels become uneven between the nodes used in the communication route and the other nodes. To ease this problem, we proposed a simple route reconstruction method that makes use of the sequence number in AODV. The proposed method can use the same control packet as the conventional AODV. We simulated the proposed method in a simple network using ns-3 and conducted a fundamental investigation into the lifetime of the first-dead node. As the result, we showed that the proposed method with multiple thresholds can prolong the lifetime of the first-dead node by 11%. The throughput of the proposed method hardly degraded compared with that for the conventional AODV. The proposed method contributes toward easing the problem of uneven battery consumption among the nodes, which occurs when using AODV.

In this paper, we analyzed the proposed method only in a simple network. Thus, it is necessary to analyze the proposed method in a complicated network as a future work. Another future work is to compare the proposed method with methods proposed in related studies that prolong the node lifetime.

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