LETTER

A New Energy-aware Source Routing Protocol for Maximization of Network Lifetime in MANET

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SUMMARY In this letter, we propose an energy-aware source routing protocol for maximizing the network lifetime in mobile ad hoc networks. We define a new routing cost by considering both transmit and receive power consumption and remaining battery level in each node simultaneously and present an efficient route discovery procedure to investigate the proposed routing cost. Intensive simulation verifies that the proposed routing protocol has similar performance to the conventional routing protocols in terms of the number of transmission hops, transmission rate, and energy consumption while significantly improving the performance with respect to network lifetime.

key words: *Routing protocol, energy-aware routing, lifetime maximization, ad hoc network*

1. Introduction

In mobile ad hoc networks (MANETs), the limited battery capacity of a mobile node (MN) affects network survivability since links are disconnected when the battery is exhausted. Therefore, a routing protocol considering the MN's energy is essential to guarantee network connectivity and prolong network lifetime [1]. Various energy-aware routing protocols have been proposed by taking into account the power consumption for transmission or the remaining battery level of the MN or both. By using such energy-aware information, various routing costs and path selection algorithms have been investigated for the purpose of improving the energy efficiency in the MANET [2]-[6].

In this letter, we propose a new energy-aware routing protocol to find a routing path with the longest lifetime in mobile ad hoc networks. While the conventional energy-aware routing protocols neglect the power consumption required to receive packets at the MN as their routing cost, the proposed routing protocol additionally considers the receiving power consumption in each MN. Namely, by considering both the transmit and receive power consumption and the remaining battery level in each node simultaneously, we design an effective routing cost that reflects a realistic node lifetime and present an efficient route discovery procedure that utilizes the proposed routing cost based on the source routing protocol. Compared to a previous work [7], we elaborate on the proposed routing algorithm and operating procedure, and also re-evaluate all the results by using the Network Simulator version 2 (NS-2) in order to validate our proposed routing protocol over a practical dynamic source routing (DSR) protocol and to provide reliable simulation results.

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2. Previous Energy-aware Routing Protocols

In this section, we introduce the representative energy-aware routing protocols.

Minimum power routing (MPR) [2] aims to minimize the total power consumed to transfer packets from the source to the destination (i.e., the energy per bit). Thus, MPR's routing strategy is expressed as

$$\min \sum P_{ij} \quad \text{for link } ij \in path \tag{1}$$

where P_{ij} denotes the power used to transmit packets from the i-th node to the j-th node and corresponds to the cost of link ij. P_{ij} is proportional to the time required to transmit a packet when the nodes use a fixed transmit power, or it depends on the path loss based on the physical distance of the link when the transmit power of the node is dynamically changed.

Minimum battery cost routing (MBCR) [3] defines the routing cost as the reciprocal of the remaining battery level of the individual node and aims at selecting the path that minimizes the sum of the cost, as follows:

$$\min \sum \frac{1}{R_i} \quad \text{for node } i \in path \tag{2}$$

where R_i indicates the remaining battery level of node i. Hence, the MBCR scheme can increase the lifetime of the selected transmission path by picking the path with the largest sum of the remaining battery level of the nodes.

Min-max battery cost routing (MMBCR) [2], [3] uses the MBCR routing cost without modification but changes only the final path selection strategy to avoid the node with the smallest remaining battery level on the path, which is expressed as

$$\min \max \left\{ \frac{1}{R_i} \right\} \quad \text{for node } i \in path. \tag{3}$$

This MMBCR causes the battery level of each node to be fair and so increases the lifetime of the overall network.

Conditional min-max battery capacity routing (CMMBCR) [3] combines MBCR and MMBCR. If the remaining battery level of all nodes on the path is greater than a certain

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threshold, it applies MBCR to increase the total battery capacity. If the battery level of one or more nodes on the path is lower than the threshold, it uses MMBCR to prolong the path lifetime. Accordingly, this routing strategy is described as

$$\begin{cases} \min \sum_{i \in path} \frac{1}{R_i}, & \text{if } \forall R_i \geq \text{threshold} \\ \min \max_{i \in path} \left\{ \frac{1}{R_i} \right\}, & \text{otherwise.} \end{cases} \quad (4)$$

The CMMBCR combines the advantages of two routing protocols; therefore, by selecting an appropriate threshold value, it can improve both the network energy efficiency and the lifetime at the same time.

Power-aware source routing (PASR) [4] and energy aware routing (EAR) [5] consider both the power consumption at the link and the remaining battery level of the node simultaneously. Their routing strategies are described as

$$\min \sum (P_{ij})^{\alpha} \left(\frac{1}{R_i} \right)^{\beta} \text{ for link } ij \in path \text{ \& node } i \in path \quad (5)$$

where α and β are positive weights. This routing cost corresponds to the reciprocal of the lifetime of link ij, and so the final routing path is selected as a path that maximizes the sum of the lifetime of all the links on the path. Because PASR and EAR consider the lifetime directly as their routing cost, their performance of lifetime can be improved as compared to the routing protocols that consider either the power consumption or the remaining battery level.

3. Proposed Energy-aware Source Routing Protocol

As seen in Sect. 2, the conventional energy-aware routing protocols utilize the power consumption required to transmit a packet through each link, which corresponds to per-link power consumption. However, practically the power consumption is generated when transmitting and receiving a packet in each node and also the receiving power consumption is comparable to the transmitting power consumption [8]. Therefore, by considering these practical power consumption factors, we propose a new routing cost based on per-node power consumption, which can reflect each node's lifetime more accurately.

3.1 Problem Description

The lifetime of the transmission path is defined as the time until one of the nodes that constitute the path exhausts its battery energy [5], [6]. Therefore, the lifetime of the end-to-end transmission path that connects the source node (S) and destination node (D) is defined as

$$L_{e2e} = \min\{L_S, \cdots, L_i, L_j, L_k, \cdots, L_D\} \quad (6)$$

where L_j denotes the lifetime of node j on the path. Thus, the objective of the proposed energy-aware routing protocol is to find an S-D path that maximizes L_{e2e}, which is described as

$$\max_{\mathbf{P}} L_{e2e} = \max_{\mathbf{P}} \min\{L_S, \cdots, L_i, L_j, L_k, \cdots, L_D\} \quad (7)$$

where $\mathbf{P} = [S, \cdots, i, j, k, \cdots, D]$ is the vector expression of node indices consisting of an S-D path.

Furthermore, to design a routing cost, we define some variables as follows:

- W: transmitted packet size (bits)
- P_{tx}/P_{rx}: constant power consumption for transmission/reception in each node (Watts)
- G_{ij}: link rate from node i to node j (bps)
- R_j: remaining battery level of node j (Joules)
- L_j: lifetime of node j (seconds)
- C_j: routing cost of node j

3.2 Design of Routing Cost

Assuming that a packet with a fixed size W is delivered via intermediate nodes i, j and k in order, on a certain S-D path, node j's required receiving time (T_j^{rx}) and transmission time (T_j^{tx}) are respectively calculated as

$$T_j^{rx} = \frac{W}{G_{ij}}, \quad T_j^{tx} = \frac{W}{G_{jk}}. \quad (8)$$

Therefore, when node j transfers a packet with size W, the energy consumptions for reception (E_j^{rx}) and transmission (E_j^{tx}) are respectively represented as

$$E_j^{rx} = P_{rx} T_j^{rx}, \quad E_j^{tx} = P_{tx} T_j^{tx}. \quad (9)$$

From Eqs. (8) and (9), the total energy consumption required to deliver a packet at node j is given by

$$\begin{aligned} E_j^{rx/tx} &= E_j^{rx} + E_j^{tx} \\ &= \frac{P_{rx} W}{G_{ij}} + \frac{P_{tx} W}{G_{jk}} = \left(\frac{P_{rx}}{G_{ij}} + \frac{P_{tx}}{G_{jk}} \right) W. \end{aligned} \quad (10)$$

Considering the remaining battery level of node j (R_j) and Eq. (10), the lifetime of node j is determined as

$$L_j = \frac{R_j}{E_j^{rx/tx}} = \frac{R_j}{\left(\frac{P_{rx}}{G_{ij}} + \frac{P_{tx}}{G_{jk}} \right) W}. \quad (11)$$

Therefore, the routing cost of node j can be defined as the reciprocal of the lifetime of node j, as follows:

$$C_j = \frac{1}{L_j} = \frac{\left(\frac{P_{rx}}{G_{ij}} + \frac{P_{tx}}{G_{jk}} \right) W}{R_j}. \quad (12)$$

Here, we can remove W because it is common for all involved nodes. Therefore, the proposed routing cost is finally defined as

$$C_j := \frac{P_{rx} G_{jk} + P_{tx} G_{ij}}{R_j G_{ij} G_{jk}}. \quad (13)$$

Note that the proposed routing cost is dependent on the remaining battery level of each node and the transmission

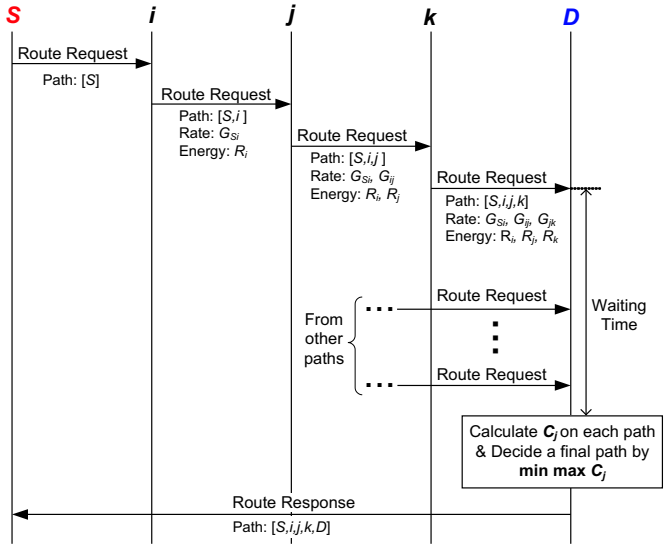


Fig. 1 Route discovery procedure for the proposed routing protocol.

rates of the incoming link and outgoing link of each node. While the conventional routing cost is based on the lifetime of each link determined by the link's transmit power consumption and the node's battery level as expressed in Eq. (5), the proposed routing cost is based on the lifetime of each node determined by the transmit and receive power consumption of each node and its battery level.

3.3 Route Discovery Procedure

To apply the proposed routing cost for the route discovery, we adopt a source routing technique, which floods route control packets on the network and delivers the necessary information to the destination. On the basis of the well-known dynamic source routing (DSR) protocol [9], the proposed routing protocol adds the information needed for calculating the proposed routing cost, i.e., the battery level of node and the link rate, in its route discovery process. Except for this, all control packets and signaling procedures related to the route discovery and maintenance conform to the original DSR protocol.

Figure 1 shows the route discovery procedure for the proposed routing protocol, which consists of the following steps:

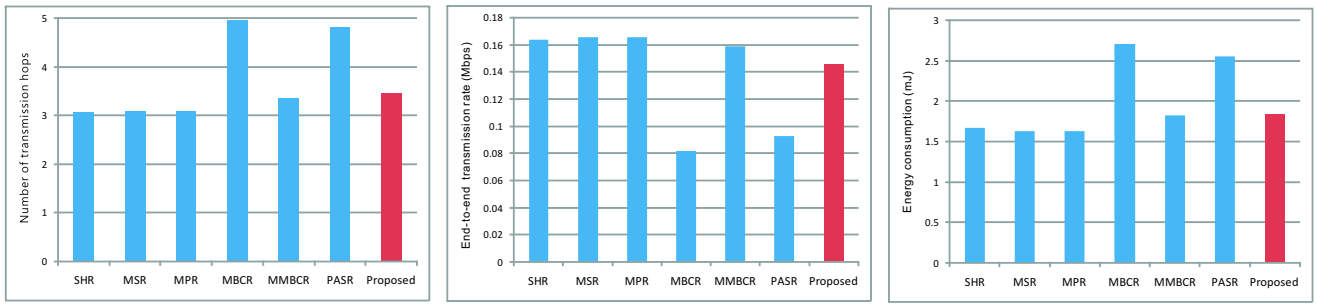
1. The source node broadcasts a route request packet to find a path to the destination node. This route request packet will collect the path information, the link rate, and the node battery level along the path. At the beginning, the source node contains only its identity (ID) information as the path information and starts to broadcast the route request packet.
2. Each node that receives the route request packet inserts 1) its own ID, 2) the link rate calculated from the link quality measured while receiving the route request packet, and 3) its remaining battery level. Thereafter, it re-broadcasts the route request packet.
3. In this way, every node that receives the route request packet floods the route request packet to the entire network after adding two more pieces of information about link rate and battery level. This enables every possible routing path to accumulate all the information required to calculate the proposed routing cost.
4. If the destination node receives a route request packet, it no longer broadcasts it and calculates the routing cost C_j for $\forall j \in path$ according to Eq. (13) by using the information of the link rate and the node battery level contained in the route request packet.
5. On receiving the first route request packet, the destination node waits for more route request packets during a certain period of time to consider different available paths. After this waiting time elapses, the destination node decides a final routing path according to the min-max C_j strategy in order to avoid a node with the shortest lifetime on the path.
6. If the destination node chooses the final routing path, it informs the source node of the chosen path information by sending the route response packet. Here, the route response packet is forwarded to the source node in the reverse order of the determined final path.

Table 1 Simulation Parameters

Parameter	Value
Number of nodes	40
Distribution of node position	Uniform in 1000 m×1000 m square
Max. communication range	300 m
Transmitted packet size (W)	1024 bytes
Number of packets transmitted on each S-D pair	100
Distribution of initial battery level of each node	Uniform(0, 100) Joules
Power consumption for tx. (P_{tx})	1.65 watt [8]
Power consumption for rx. (P_{rx})	1.40 watt [8]
Distance-based path loss [11]	$-128.1-37.6log_{10}(d)$ [dB], d in km
Channel bandwidth	10 MHz
Noise figure	9 dB
Waiting time at the destination	60 s
Number of simulation trials	1000

4. Result and Discussion

The performances of the proposed routing protocol are compared with those of the conventional energy-aware routing protocols of MPR, MBCR, MMBCR, PASR (addressed in Sect. 2), shortest hop routing (SHR) that chooses the path with the smallest number of hops, and max sum rate (MSR) routing that chooses the path whose sum of link rates is the highest [1]. We verify the performance of the proposed routing protocol using the Network Simulator version 2 (NS-2) by modifying the DSR source code [10]. Table 1 shows the simulation parameters used. The considered simulation scenario is as follows. First, we randomly select source and destination nodes among 40 nodes deployed randomly in 1000 m × 1000 m square [12]. Then, a routing path between this source and destination pair is established by each



(a) Number of transmission hops (b) End-to-end transmission rate (c) Energy consumption

Fig. 2 Performance comparisons of routing protocols.

routing protocol. The source node sends 100 packets to the destination node in sequential order as soon as it receives an ACK packet from the destination node. The size of each packet is 1024 bytes. If this packet transmission is completed, the routing path is removed and the new source and destination pair is randomly selected. This process is repeated until battery-exhausted nodes occur.

Figure 2 shows the performance of each routing protocol with respect to (a) number of transmission hops, (b) end-to-end transmission rate, and (c) energy consumption needed to deliver a packet from source to destination. In terms of the number of transmission hops, SHR, which always chooses the shortest path, shows the smallest number of transmission hops, and both the MSR and the MPR show similar performance. On the other hand, MBCR, which uses a routing cost based on the remaining battery level, and PASR, which considers the link lifetime as its routing cost, increase the number of transmission hops because they use the min-sum path selection strategy. In the case of the proposed scheme, the number of transmission hops increases slightly as compared to the SHR scheme.

Regarding the end-to-end transmission rate, MSR, which operates to maximize the sum rate, shows the best performance, and MPR shows the same performance because it determines the power consumption cost based on the transmission rate. The other schemes show a decreased performance because they choose nodes with high battery level instead of high transmission rate.

With respect to the energy consumption, MPR, which select the path to minimize the sum of power consumption, shows the best performance, and both SHR and MSR show similar performance. However, MBCR and PASR, which consider the battery level and the link lifetime, respectively, increase the total energy consumption because they use the increased number of transmission hops. On the other hand, the proposed scheme shows a similar energy consumption to the MPR scheme.

Figure 3 shows the network lifetime (the time taken until x nodes die out due to the battery exhaustion) under the various routing protocols including the proposed scheme. From the perspective of lifetime, the proposed scheme exhibits longer lifetime than the other schemes and has a gain of minimum 10% and maximum 20% compared to MMBCR. This is because the proposed scheme considers both the remaining battery level and the power consumption required for each node to transmit and receive packets suitably from the viewpoint of the actual lifetime of each node. On the other hand, the conventional routing protocols shows decreased lifetime because they are based on the typical link lifetime and do not consider the receiving power consumption in each node.

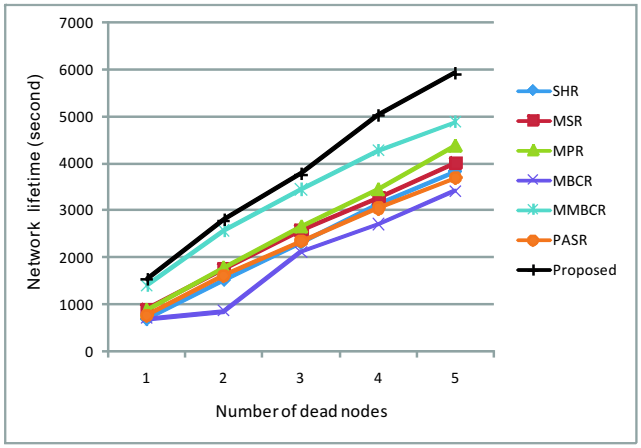


Fig. 3 Network lifetime (the time taken until x nodes die out) under the various routing protocols.

5. Conclusion

We proposed an energy-aware source routing protocol to maximize the lifetime of the transmission path. We designed an effective routing cost and an efficient route discovery procedure, which are based on both the transmit and receive power consumed at each node and the remaining battery level of each node in order to reflect a realistic node lifetime. The NS-2 simulation showed that the proposed scheme has similar performance to the conventional routing schemes in terms of the number of transmission hops, end-to-end transmission rate, and energy consumption, but offers superior performance in terms of lifetime. We believe that the proposed routing protocol can be applied to MANETs requiring high energy efficiency through a simple modification of the existing DSR protocol.

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