An On-demand Energy-efficient Routing Algorithm for Wireless Ad hoc Networks *

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Abstract. Ad hoc networks are non-infrastructure networks which consist of mobile nodes. Since the mobile nodes have limited battery power, it is very important to use energy efficiently in ad hoc networks. In order to maximize the lifetime of ad hoc networks, traffic should be sent via a route that can be avoid nodes with low energy while minimizing the total transmission power. In addition, considering that the nodes of ad hoc networks are mobile, on-demand routing protocols are preferred for ad hoc networks. However, most existing power-aware routing algorithms do not meet these requirements. Although some power-aware routing algorithms try to compromise between two objectives, they have difficulty in implementation into on-demand version. In this paper, we propose a novel on-demand power aware routing algorithm called DEAR. DEAR prolongs its network lifetime by compromising between minimum energy consumption and fair energy consumption without additional control packets. DEAR also improves its data packet delivery ratio.

1 Introduction

A mobile ad hoc network is a collection of wireless devices that come together to form a self-organizing network without any support from the existing fixed communication infrastructure. In such a network, each device plays the role of a router and has limited battery energy. In addition, the network topology can constantly change. Thus, it is widely accepted that conventional routing protocols are not appropriate for mobile ad hoc networks, and, consequently, the design of routing protocols for such networks is a challenging issue taking power factor into consideration.

To reduce the energy consumption in mobile devices, there have been efforts in physical and data link layers as well as in the network layer related to the routing protocol. The physical layer can save energy by adapting transmission

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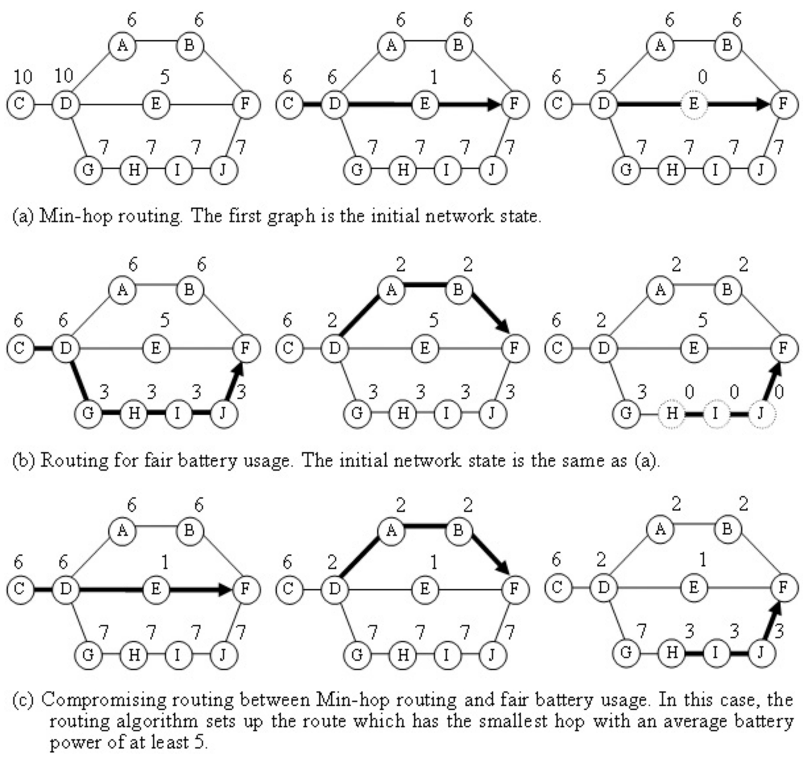
power according to the distance between nodes. At the data link layer, energy conservation can be achieved by sleep mode operation.

The purpose of power-aware routing protocols is to maximize the network lifetime. The network lifetime is defined as the time when a node runs out of its own battery power for the first time [1]. If a node stops its operation, it can result in network partitioning and interrupt communication. The power-aware routing protocols should consider energy consumption from the viewpoints of both the network and the node levels. From the network point of view, the best route is one that minimizes the total transmission power. On the other hand, from the viewpoint of a node, it is one that avoids the nodes with lower power. It is difficult to achieve these two objectives simultaneously. Minimizing the total energy consumption tends to favor min-hop routes. However, if the min-hop routes repeatedly include the same node, the node will exhaust its energy much earlier than the other nodes and the network lifetime will decrease.



(a) Min-hop routing. The first graph is the initial network state.

(b) Routing for fair battery usage. The initial network state is the same as (a).

(c) Compromising routing between Min-hop routing and fair battery usage. In this case, the routing algorithm sets up the route which has the smallest hop with an average battery power of at least 5.

Fig. 1. Lifetimes of different routing algorithms. 4 data packets are delivered for each session in order of C→F, D→F and H→F

Figure 1 (a) illustrates this problem: A node E acts as a relaying node in two routes, thus it spends its energy earlier. On the other hand, a consideration on the energy level of each node may select longer-hop routes, which spend more energy. Figure 1 (b) exemplifies the problem when a routing algorithm sets up a route with the largest residual battery energy. Therefore, the power-aware routing protocols should have a mechanism to balance the two objectives. Figure 1 (c) shows that the scheme that skillfully chooses routes can have better performance. This paper focuses on how to balance the two objectives.

In a wide sense, ad hoc routing algorithms can be classified into the pro-active and the on-demand routing algorithms. The on-demand routing algorithms [2][3] start to find out the suitable route when a route is requested while the pro-active scheme [4] exchanges routing information periodically and generates the routing table in advance. Paper [5] shows that the on-demand routing outperforms the pro-active in terms of both delivery ratio and routing overhead. This is because it is difficult to find out the proper exchange rate of control packets, which depends on the mobility. The pro-active scheme has the possibility that some routing information exchanged is useless. That is, a slow exchange rate can make the routing information stale, and a fast rate results in excessive routing overhead. Therefore, it is a natural choice to design a power-aware routing protocol based on the on-demand scheme.

The Max-min zP_{min}[1] and CMMBCR [6] can be classified as routing protocols that balance two conditions for the lifetime. The Max-min zP_{min} algorithm has difficulty in implementing into the on-demand scheme. On the other hand, the CMMBCR needs to add the overhead of control packets for the on-demand version, and also it is not easy to decide the optimal threshold value that determines the operation modes. This paper proposes an on-demand power-aware routing algorithm called DEAR (Distributed Energy-efficient Ad hoc Routing). Our proposed routing algorithm balances between minimum transmission energy consumption and fair node energy consumption in a distributed manner. This goal is achieved by controlling the rebroadcast time of RREQ packets. In addition, we design a mechanism of estimating the average energy level of the entire network without additional control packets. The estimated average energy is useful to adaptively control the rebroadcast time.

The rest of the paper is organized as follows. Section 2 reviews typical power-aware routing algorithms and discusses the pros and cons from the viewpoint of the network lifetime. In Section 3, we present our proposed power-aware routing algorithm in detail. Section 4 describes the simulation results and performance comparison. Finally, we conclude this paper in Section 5.

2 Existing Power-aware Routing Protocols

Conventional routing protocols [2][3][4] for ad hoc networks select the routes under the metric of the minimum hop count. Such min-hop routing protocols can use energy unevenly among the nodes and thus it can cause some nodes to spend their whole energy earlier as indicated in Section 1. As shown in the following examples, the feature of a power-aware routing protocol mainly relies on its metric. Candidates for the power-aware routing metric are considered in

[7], and the performance of the power-aware routing protocols with different metrics is evaluated in [6].

MTPR (Minimum Total Transmission Power Routing) sets up the route that needs the lowest transmission power among possible routes. This scheme can be applied in the environment where transmission power adjustment is available. Because the required transmission power is proportional to the n-th power of the distance between nodes, this scheme prefers shorter links and has the tendency to select the route with more hops. However, MTPR has some problems. It turns out that the adaptation of transmission power can bring a new hidden terminal problem [8]. The hidden terminal problem makes more collision, and it results in more energy consumption due to retransmission. Even if there is an algorithm proposed for the problem, it can not be implemented with the current technology. And, MTPR has a similar problem to min-hop routing in that it makes no efforts to use energy evenly among nodes.

MBCR (Minimum Battery Cost Routing) tries to use battery power evenly by using a cost function which is inversely proportional to residual battery power. One possible choice for the cost function of a node i is given as $f(b_i) = \frac{1}{b_i}$, where b_i is the residual battery energy of a node i. The total cost for a route is defined as the sum of costs of the nodes that are the components of the route, and MBCR selects a route with the minimum total cost. This method seems to extend the network lifetime because it chooses the route composed of the nodes whose remaining battery power is high. However, because it considers only the total cost, the remaining energy level of an individual node may hardly be accounted for. That is, the route can include a node with little energy if the other nodes have a plenty of energy [6].

To prolong the lifetime of an individual node, MMBCR (Min-Max Battery Cost Routing) introduces a new path cost, which is defined as $R_j = \max_{i \in route\_j} f(B_i)$, and it selects the route with the minimum path cost among possible routes. Because this metric takes into account the remaining energy level of individual nodes instead of the total energy, the energy of each node can be evenly used. However, this scheme can set up the route with an excessive hop count and then consume a lot of total transmission energy.

CMMBCR (Conditional Max-Min Battery Capacity Routing) [6] tries to balance the total transmission power consumption and the individual node power consumption. This algorithm operates in two modes according to the residual battery power. If there are nodes that have more battery power than threshold power, it applies MTPR to the nodes. Otherwise, it mimics MMBCR. Roughly speaking, when battery power is plentiful, it minimizes the total energy consumption like MTPR, and in the other case it considers the nodes with lower energy like MMBCR. The performance of CMMBCR is heavily influenced by the threshold value. In a case where the threshold value is 0, it is identical to MTPR. As the threshold value grows by infinity, it is transformed into MMBCR [9].

The max-min $zP_{\min}$ algorithm [1] is another balancing power-aware routing protocol. This scheme selects the route that maximizes the minimal residual power fraction under the constraint of the total power consumption. Total power consumption is limited to z times the minimum total transmission power. This algorithm is much more complex than the others mentioned before, and it is not easy to choose a suitable z value.

3 Distributed Energy-efficient Ad hoc Routing

3.1 Basic idea

Generally in on-demand routing protocols [2][3], the source floods an RREQ (Route-Request) packet to search a path from source to destination. The destination node receives the RREQ packet and unicasts an RREP (Route-reply) packet to the source to set up a path. Likewise, our proposed DEAR is an on-demand algorithm. DEAR doesn't use additional control packets to acquire necessary information for power aware routing but utilizes RREQ packets which are already used in on-demand routing protocols. DEAR only requires the average residual battery level of the entire network, which can be obtained without any control packets other than RREQ packets.

In our proposed algorithm, intermediate nodes control the rebroadcast time of the RREQ packet, where retransmission time is proportional to the ratio of average residual battery power of the entire network to its own residual battery power. In other words, nodes with relatively larger battery energy will rebroadcast RREQ packets earlier. Because on-demand routing protocols drop duplicate RREQ packets without rebroadcasting them, DEAR can set up the route composed of the nodes with relatively high battery power.

3.2 Average residual battery power Estimation

Basically the nodes use their residual battery power for the rebroadcast time of RREQ packets. If the time is determined only by the nodes' absolute residual battery power, then the retransmission time will increase as time passes by. Therefore, the relative measure should be used.

As a relative measure, we used the average residual battery power of the entire network. The exact value of this average power can be acquired by periodic control packets, but using periodic control packets isn't an on-demand method and it also consumes more energy.

To estimate the average energy, our proposed algorithm uses only RREQ packets that are already used in on-demand routing. For this end, $\overline{R}$ and N fields are added to the packet header, where $\overline{R}$ is the average residual battery power of the nodes on the path and N is the number of hops that the RREQ packet has passed. The mechanism to obtain the estimated average value is as follows.

1. First, the source records its own battery power to the $\overline{R}$ field, and sets the N to 1, and broadcasts the RREQ packet.

2. Assume that a node i has received an RREQ packet, and the node i's residual battery power is B_i and the $\overline{R}$ value of the RREQ packet is $\overline{R}_{old}$. Then the average residual battery power, $\overline{R}_{new}$, of new route that includes the node i is as following

$$\overline{R}_{new} = \frac{\overline{R}_{old} \times N + B_i}{N + 1} \quad (1)$$

   Before the node i rebroadcasts the packet, it updates $\overline{R}$ to $\overline{R}_{new}$ and increases the value of N by one. This step is not executed for duplicate RREQ packets.
3. Whenever a node i receives an RREQ packet, it calculate the average residual battery power of the network by the following equation.

$$\tilde{E}_{new} = (1 - \alpha)\tilde{E}_{old} + \alpha\overline{R}_{old} \quad (2)$$

   where α is the weighting factor of the moving average. The α is set to 0.75 in our simulations.

3.3 Rebroadcast time control

A node i determines its rebroadcast time T as follows.

$$T = D \times (\frac{\tilde{E}}{B_i}) \quad (3)$$

$\tilde{E}$ is the estimated average power, B_i is its own residual power, and D is a constant to scale the retransmission time. According to equation (3), if the residual battery power B_i is smaller than the average network residual power $\tilde{E}$, then the retransmission time T will be longer, and if B_i is larger then vice versa. So if the individual battery power B_i is larger than the average, then the node i would tend to be selected as a member of the route, which results in fair energy consumption among the nodes. When the residual battery power variation is small, most nodes have a similar retransmission time. In that case, the route with a smaller hop count will be selected. This shows that DEAR compromises between the min-hop path and the fair energy consumption path.

4 Performance Evaluation

We used NS (Network simulator version 2.1b8a) [10] to compare the performance of DEAR with that of existing power-aware routing algorithms.

As mentioned before, on-demand routing protocols are adequate for ad hoc network environments. Therefore we performed simulation on the power-aware routing algorithms that could be implemented to on-demand routing protocols.

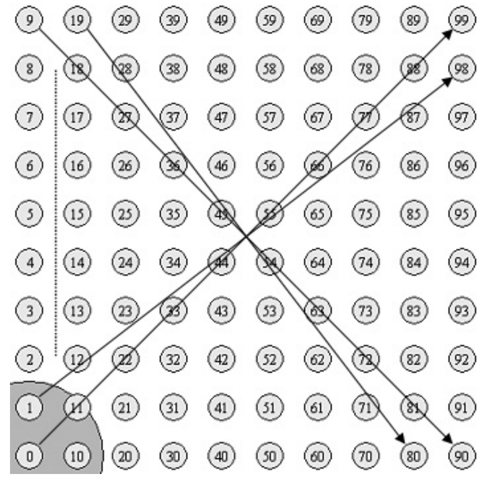


Fig. 2. The 100-node topology

4.1 Simulation model

We used three kinds of scenarios. In the all scenarios, the same topology shown in Figure 2 is used at the initial point, where 100 nodes are uniformly distributed and nodes are 150m apart. The initial energy of all the nodes is 0.25J. The transmission power is 200mW and the receiving power is 100mW.

In the first scenario, all the nodes are stationary and 36 UDP sessions are sequentially generated. Each session transmits 100 CBR packets for 5 seconds. As shown in Figure 2, the pair of a source node and a destination node is sequentially determined for the edge nodes, starting from node 0 in a clockwise direction.

The second scenario gives mobility to the nodes, to be similar to actual situations. Each node pauses for 60 seconds and moves to a random position at the maximum speed of 2m/s (average 1m/s).

In the third scenario, the source and destination nodes of 36 different sessions are randomly chosen. The initial energy of all the nodes is set to 0.2J. The remaining conditions are the same as those of the first scenario.

4.2 Simulation results

Figure 3 shows the results of the first simulation. Figure 3 (a) shows the number of nodes that run out of their battery power as a function of time. The time when the first node dies indicates the lifetime of the network, and the slope of the graph shows the fairness of energy consumption among nodes. If the slope is small, it means that the variation of the lifetime of the nodes is large. That is, the use of batteries is unfair. On the contrary, if the slope is steep, it means that the battery power of the nodes has been fairly used.

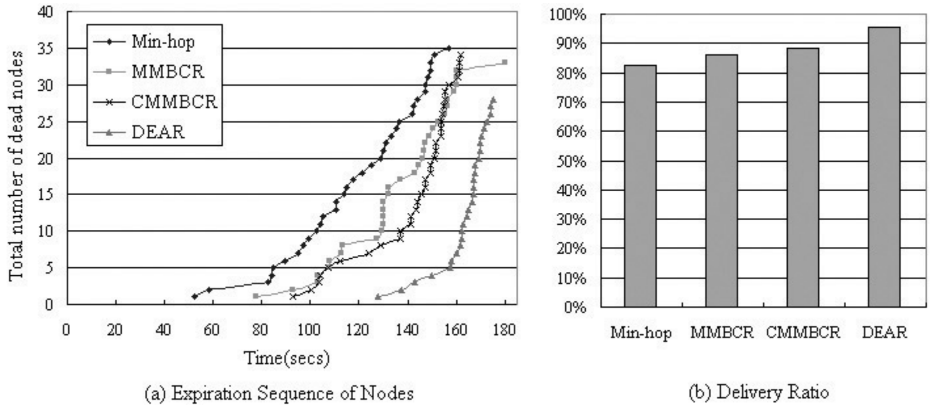


Fig. 3. Results in the stationary environment

Comparing the network lifetime of each algorithm, the min-hop had the shortest lifetime of 52 seconds. Min-hop routing also had the smallest slope, which means the energy was consumed unfairly among the nodes. Although MMBCR extended the network lifetime to approximately 78 seconds by using battery power evenly among the nodes, the lifetime extension wasn't so good since it tended to select long paths with many hops to guarantee fairness. And because the on-demand scheme of MMBCR can not consider all the possible paths, it can deteriorate performance.

CMMBCR minimized the network energy consumption by using the min-hop routing when residual battery power was larger than the threshold value, and extended its network lifetime to 93 seconds. As CMMBCR used additional control packets, the network lifetime didn't increase dramatically compared to MMBCR. However the fairness of CMMBR increased.

DEAR showed better performance than the others. The network lifetime increased to 128 seconds which is about 2.5 times longer than that of min-hop routing. The network lifetime is about 1.4 times longer than that of CMMBCR. This improvement is due to the fact that DEAR compromised between the min-hop routing and the fair energy consumption without additional control packets.

Figure 3 (b) shows a comparison of the delivery ratio among power-aware routing algorithms. We can see that the better power-aware routing algorithms also have a better delivery ratio. DEAR showed the highest delivery ratio of about 95%, which is approximately 13% higher than that of the min-hop routing, and approximately 7% higher than that of CMMBCR. The reason why the delivery ratio is proportional to the performance of power-aware routing is because the nodes with less residual battery power are excluded from the route in power-aware routing algorithms. If the established route contains a node which has small residual battery power, the node will consume all its battery power. Then the route will break in the middle of data packet delivery and the remaining data packets will be lost. Therefore, the better the performance of power-aware routing, the higher the reliability of the route and the delivery ratio.

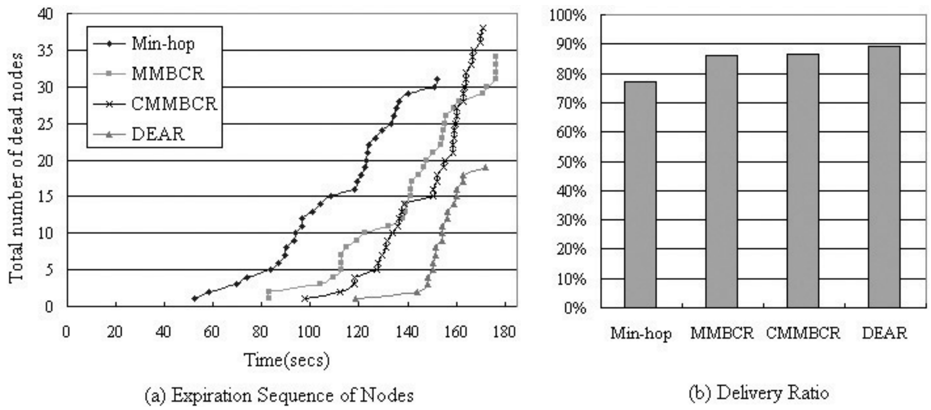


Fig. 4. Results in the mobile environment

The result of the second simulation is shown in Figure 4. When nodes have mobility, DEAR also showed better performance.

Table 1. Results in the random traffic environment

	Min-hop	MMBCR	CMMBCR	DEAR
Network lifetime	96.5s	145.9s	150.1s	170.2s
Delivery ratio	95.5%	97.6%	98.7%	99.8%

Table 1 shows the result of the third simulation which reflects a more realistic traffic pattern. In this case, DEAR also outperforms the others.

5 Conclusion

Conventional power-aware routing algorithms require information such as network topology and residual power to set up an energy efficient route. However, it is not explicitly mentioned how to obtain such information. It would be easy to obtain such information if pro-active routing is used, but pro-active routing wouldn't be suitable for ad hoc networks.

Because most existing power-aware routing algorithms are designed without considering the implementation of on-demand protocols, some algorithms require additional control packets for the on-demand version, which cause energy consumption.

In this paper, we proposed a new power-aware routing algorithm called DEAR. DEAR is an on-demand routing protocol which sets its route in a distributed manner. DEAR only requires average residual battery level of the entire network, which can be obtained without other control packets except for RREQ packets. When RREQ packets are broadcast, the rebroadcast time is determined by the amount of time which is proportional to the ratio of average residual battery power of the entire network to its own residual battery power. As a result, DEAR selects nodes that have relatively abundant battery energy. Since the rebroadcast time dynamically varies according to residual battery power, DEAR keeps a balance between min-hop routing and fair battery consumption.

The simulation results showed several advantages of DEAR over other existing algorithms in terms of performance. DEAR not only prolongs the network lifetime but also improves the delivery ratio by selecting a more reliable path.

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