Energy-Aware Routing with Limited Route Length for Multimedia Applications*

Cheolgi Kim[1], Kisoo Chang[2] and Joongsoo Ma[1]

[1] Information and Communications University, Daejeon 305-732, Korea
{cheolgi, jsma}@icu.ac.kr
[2] Samsung Advanced Institute of Technology, Suwon 449-712, Korea
kschang@samsung.com

Abstract. In ad hoc networks, energy preservation on communications is crucial because most of nodes are battery-powered. On the other hand, communication delay is an important factor of real-time communications. Since energy-aware routes commonly have long route lengths, which commonly result long communication delays, a trade-off has to be made on route setup between energy preservation and communication delay. Moreover, long route length also incurs high packet drop rate, which causes low reliability and high retransmission cost. We propose energy-aware route search algorithms with limited route length (EAR-LRL). We show that the computational complexities of the centralized version of our algorithms are polynomial. The simulation results show that EAR-LRL generates routes with limited route length with resonably low total transmission power.

1 Introduction

In ad hoc networks, power consumption is a critical issue because most of the participating nodes are supposed to be battery-powered. Even though the energy optimization algorithms in centralized networks have been widely investigated, most of them cannot be directly adapted to ad hoc networks. In centralized networks, base stations are exploited for energy saving of subscriber stations in many aspects, while ad hoc networks hardly have a device which is able to sacrifice itself for other nodes' energy preservation. Thus, the collaborating methods are investigated for energy saving in ad hoc networks.

One of the mostly considered approaches is transmission power control in ad hoc networks. 802.11 specifications are based on fixed power transmission because of the limitation of conventional CSMA/CA. The receiving power is given by

$$P_R = \frac{\zeta P_T}{d^K} \tag{1}$$

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where ζ is a shadowing coefficient, P_T is transmission power level, d is the distance between the nodes and K is a path loss coefficient, usually larger than 2 [1]. Given BER, transmission power is a function of the distance between the source and the destination when transmission power control is adopted. As a result of Eq. 1, the transmission power commonly decreases to a quarter when a distance between a couple of nodes decreases to a half.

To maximize the effect of power control, a lot of approaches exploit intermediate nodes as much as possible to relay the packets from source to destination while conventional routing algorithm is commonly looking for shortest hop routes. Suppose that N nodes are distributed in a line having equal distance between nearby nodes, and the leftmost node is the source and the rightmost one is the destination. The transmission power when the source delivers a packet directly to the destination, must be at least N times higher than total transmission power when all deployed nodes participate the packet relay with transmission power control by Eq. 1. As long as appropriate power control MAC is exploitable, the power efficiency with N relay nodes is up to N times better than direct transmission due to Eq. 1. We call the routing algorithm exploiting intermediate node to relay a packet for energy preservation, as *energy-aware routing*.

There are two problems in energy-aware routing: high error rate, and long end-to-end delay. If a network builds a route optimizing the total transmission power, the number of hops inherently becomes large. If the packet error rate per hop is assumed to be same per each hop, the total error rate is destined to be linearly increased when the number of hops is increased. Moreover, the end-to-end delay will basically increase as well not only because of longer route length but also because of high error rate. Some work [1, 2] has shown that the higher error rate affects the power consumption as well. As a result, the energy per route is expected to increase with route length from some point of route length, due to the increasing error rate.

These problems are amplified in VoIP and multimedia streaming applications. In VoIP as well as multimedia applications, the packet becomes useless if the delivery of a packet exceeds the deadline. VoIP is a killer application in military ad hoc communication system, which is usually urgent and time-critical. Moreover, the proportion of multimedia applications is becoming crucial in ad hoc networks.

To cope with the problems, we propose power-aware routing protocols with limited route length. We strictly bound the route length to guarantee the packet delivery time or better power property. We show that the computational complexities of the centralized algorithms are polynomial, and extend to the distributed versions.

2 Related Work

There have been challenges to overcome fixed transmission power MAC. Power control MAC has been adopted to networks in different situations [3–5] and S. Agarwal et al. proposed and evaluated power control loop MAC in group mobility environment [3], S. Wu et al. extended the transmission power control to multi-channel ad-hoc networks [4]. T. A. ElBatt et al. proposed TDMA-based distributed packet scheduling algorithm with power control to reduce the interference and power consumption in ad hoc networks [5].

Some authors addressed the relationship between the transmission power control and RTS/CTS mechanism. RTS/CTS packets must be transmitted with highest power to announce the data packet transmission to all neighborhoods while data packet would have adjusted transmission power. E.-S. Jung et al. addressed that the nodes in the carrier sensing range and not in the transmission range will only sense RTS/CTS but data packets so they can try transmission during data packet exchange [6]. They proposed periodic power control to minimize such a problem. A. Muqattash et al. proposed POWMAC, which enhances the network capacity by allowing simultaneous transmissions from the neighbor nodes as long as the incurred interference is endurable [7]. RTS/CTS/DTS messages, replacing conventional RTS/CTS messages, have power information of following data transmission so that other nodes overhear them and decide if they communicate generating endurable interference. Their proposal significantly outperforms original 802.11 in clustered environment.

The energy-aware routing proposals to minimize the transmission power consumption have been proposed, as well [8–13]. Some work has been devoted to estimate the total transmission power in a distributed way [11, 14, 12]. C. Gentile et al. addressed high mobility environment by kinetic minimum-power routing in [12] while others cope with stationary environment. They have exploited the velocity of a node for the future position estimation. Clustering has been considered as a candidate to reduce the management cost by exploiting locality of the participating nodes because energy-aware routing algorithms need to manage a lot of information changing frequently [8, 13]. C.-K. Toh presented a routing algorithm having low total transmission power and long battery life together by max-min approach in [10].

T. A. ElBatt et al. investigated the effect of transmission power control. They influenced the performance varies with the transmission power due to the interference range, retransmission ratio, cluster isolation and the number of hops [1]. S. Banerjee et al. also argued analytically that the route with many relay nodes do not always perform better with the proper metric including the packet error recovery efforts in [2]. They showed there is optimal number of relay nodes when we adapt *end-to-end retransmission model*. A few relay nodes do not exploit the potential reduction in the transmission energy, while a number of relay nodes cause the overhead of retransmissions to dominate the total energy budget.

3 Problem Statement

The goal of EAR-LRL is to minimize the total transmission power cost not to exceed a given route length. The reason why our approaches limit the number of hops is two folds: (1) When we add more relay nodes in the middle of the route, the end-to-end retransmission cost increases, while the total transmission cost, regardless retransmission, commonly decreases. The transmission cost and the retransmission cost make a kind of trade-off relationship with respect to the route length. S. Banerjee analyzed and showed that there exists an optimal route length in terms of the total transmission cost including retransmission cost with the given parameters in [2]. By limiting the route length to the analyzed optimal value, we can decrease the complexity of the algorithm. (2) Moreover, some real-time applications need to limit the end-to-end delay for the quality of service. Even though the end-to-end delay is not represented as a function of route length, it is highly correlated with the route length. Therefore, the delay requirement can be fairly achieved by the limit of the route length. We describe and formalize the problems in the following subsections.

Optimal route length regarding retransmission cost A couple of transmission energy models are considered in our proposals: *typical energy model* and *retransmission-aware energy model*. Typical energy model assumes that there is no packet drop during packet delivery, so does not consider the retransmission cost, while retransmission-aware energy model considers the cost incurred by packet losses and retransmissions.

Suppose that $G = (V, E)$ represents a graph with a set of nodes, V and a set of communication links, E. In a *typical energy model*, the total expected transmission power of a route is given by

$$E_{\mathrm{typ}}(X) = \sum_{i=1}^{n} E(x_{i-1}, x_i) = \alpha \sum_{i=1}^{n} d^K_{x_{i-1},x_i} \tag{2}$$

where $E(\cdot)$ is energy consumed in a link or a route, X is a route $[x_0, x_1, ..., x_N]$ from node x_0 to node x_N, $d_{i,j}$ is a distance between node i and j, and α is a coefficient in simplified energy equation in one hop, $E(i, j) = \alpha d^K_{i,j}$ derived from Eq. 1 given BER or receiving power. In the typical energy model, route with relay nodes, which has longer route length with short individual links, may have smaller expected energy as discussed in Sect. 1.

In *retransmission-aware energy model*, which considers the cost of packet losses and retransmissions, the total expected energy required in the reliable transmission of a single packet is given by

$$E_{\mathrm{ret}}(X) = \frac{\sum_{i=1}^{N} \alpha d^K_{x_{i-1},x_i}}{(1 - p_l)^N} \tag{3}$$

where p_l is the packet error rate in each hop. S. Banerjee simplified the problem by adopting the line topology, [2]. In the topology, the total expected energy is simplified by

$$E_{\mathrm{ret}} = \frac{\alpha D^K}{N^{K-1} \cdot (1 - p_l)^N}. \tag{4}$$

From Eq. 4, the optimal route length is given by

$$N_{\mathrm{opt}} = \frac{K - 1}{-\log(1 - p_l)}. \tag{5}$$

Note that the optimal route length depends only on K and p_l, not on D. Thus, the nodes can easily derive the optimal route length with K and p_l, which can be obtained from the communication environment and link status.

Multimedia application case Most of multimedia applications have delay constraints due to the real-time and interactive properties. We suppose that the end-to-end delay is proportional to the route length. S.-T. Sheu et al. have insisted that longer route length does not directly mean longer delay [15]. The reason is two folds: (1) longer link will have lower SINR with a fixed transmission power MAC (2) and the link with longer distance will contend with more nodes due to the larger interference area. The first fold can be ignored in our work because we assume that nodes control their transmission powers. The second one can be significant in the high contention environment. However, Most of ad-hoc network protocols have QoS-aware MACs, which provide higher priority to the time-critical applications. For example, applications with high priority can have shorter inter frame spacing time, or have reserved slot for communications. Thus, we suppose that the one-hop delay would hardly depend on the link distance for the multimedia application. However, route length inherently affects the communication delay. With this assumption, we can easily derive the maximum route length in terms of the time constraints of a certain application.

4 Energy-aware Ad Hoc Route Search Algorithms with Limited Route Length

In this section, we show that the computational complexity of the EAR-LRL for one source node to all other nodes as destinations based on typical energy model is $O(nhk)$ where n is the number of nodes, h is the maximum route length and k is the maximum communication link degree of a node. Moreover, we also show that the complexity of the EAR-LRL algorithm from one source node to all other nodes as destinations based on retransmission-aware energy model is $O(nh^2k)$. Notice that operation $[a; b]$ makes a new sequence of nodes concatenating a and b where each a and b can be either a single node or a sequence of nodes. A sequence of nodes and a route are identical.

4.1 Route search algorithm based on typical energy model

Lemma 1. *The minimum energy route based on the typical energy model with route length limited to h between node u and v, $\bar{R}_h(u,v)$ is given by*

$$\bar{R}_h(u,v) = [\bar{R}_{h-1}(u,w); v] \tag{6}$$

such that w minimizes $E_{typ}([\bar{R}_{h-1}(u,w)); v])$ and $(w,v) \in E$

Proof. Let us represent $\bar{R}_h(u,v)$ as $[\hat{R}(u,w); v]$. Then, the second last node of the route is w. For a contradiction, we assume that $\hat{R}(u,w) \neq \bar{R}_{h-1}(u,w)$. Now, we have

$$E_{\mathrm{typ}}(\bar{R}_{h-1}(u,w)) > E_{\mathrm{typ}}(\hat{R}(u,w)). \tag{7}$$

However, $\bar{R}_{h-1}(u,w)$ is the minimum energy route from u to w with limited route length $(h-1)$. As $\hat{R}(u,w)$ must have a route length at most $h-1$, Eq. 7 conflicts with the definition of $\bar{R}_{h-1}(u,w)$. □

Lemma 1 is used for EAR-LRL based on typical energy model. As long as the communication environment is good enough so MAC protocol like ARQ guarantees sufficiently high probability of hop-by-hop delivery, we can use typical energy model because retransmission probability is supposed to be negligible. EAR-LRL based on typical energy model is simpler than that based on retransmission-aware energy model. Fig. 1 shows the centralized EAR-LRL algorithm from node u to all other nodes based on typical energy model.

function $ROUTE \leftarrow EAR\_LRL\_TYP(u,h)$
  if $h = 0$ **then**
    $ROUTE \leftarrow [u]$; **return**;
  end

  $ROUTE \leftarrow \varnothing$
  $ROUTE' \leftarrow EAR\_LRL\_TYP(u,h-1)$
  $V' \leftarrow \{v \in V | [u;\cdots;v] \in ROUTE'\}$
    %% V' is set of reachable nodes in $(h-1)$ hops from u
  $V'' \leftarrow V' \cup \{w \in V | (v,w) \in E \text{ for } \forall v \in V'\}$
    %% V'' is set of reachable nodes in h hops from u

  foreach $v \in V''$
    $R \leftarrow \{r \in ROUTE' | r = [u;\cdots;w] \text{ and } (w,v) \in E\}$
    find one $min\_r \in R$ $s.t.$ $E_{\text{typ}}([min\_r;v]) = \min_{r \in R} E_{\text{typ}}([r;v])$
    $ROUTE \leftarrow ROUTE \cup \{[min\_r;v]\}$
  end

Fig. 1. EAR-LRL algorithm based on typical energy model

Note that the EAR-LRL algorithm from one source node to all destinations is $O(nhr)$ where n is number of nodes, h is the route length limit, and r is maximum link degree per node.

4.2 EAR-LRL algorithm based on retransmission-aware energy model

EAR-LRL algorithm based on the typical energy model cannot be directly used on the retransmission-aware algorithm because the cost function is more complicate (see Eq. 4).

Lemma 2. *The minimum energy route based on the retransmission-aware energy model with route length limited to h between node u and v, $R_h(u,v)$ is given* *by*

$$R_h(u,v) = [R';v] \ \textit{where}\ R' \in \bigcup_{(w,v)\in E \ \textit{and}\ 0\le i<h} R_i(u,w) \quad (8)$$

such that R' minimizes the total energy cost $E_{ret}([R';v])$.

Proof. Assume that $R_h(u,v) = [R';v]$ and $R' \notin \bigcup_{(w,v)\in E \text{ and } 0\le i<h} R_i(u,w)$. Moreover, suppose that j is the route length of R' and R' is represented as $[u;\cdots;w]$, so let w be the destination of R'. The assumption can be simplified as $R' \neq R_j(u,w)$ with the definition of j and w. The total energy consumption based on retransmission-aware energy model of R' and $R_j(u,w')$ is given by

$$E_{\text{ret}}([R';v]) = \frac{E_{\text{ret}}(R')}{1-p_l} + \frac{\alpha d^K_{w',v}}{(1-p_l)^j}$$

$$E_{\text{ret}}([R_j(u,w');v]) = \frac{E_{\text{ret}}(R_j(u,w'))}{1-p_l} + \frac{\alpha d^K_{w',v}}{(1-p_l)^j}$$

respectively. The assumption declares that $E_{\text{ret}}([R';v])$ must be smaller than $E_{\text{ret}}([R_j(u,w');v])$. However, it conflicts with $E_{\text{ret}}(R') > E_{\text{ret}}(R_j(u,w'))$ by the definition of $R_j(\cdot)$. □

Lemma 2 is used for EAR-LRL algorithm based on the retransmission-aware energy model. Fig. 2 shows the algorithm.

```
function ROUTE(0···h) ← EAR_LRL_RET(u,h)
    if h = 0 then
        ROUTE ← [u]; return;
    end

    ROUTE(h) ← ∅
    ROUTE(0...h−1) ← EAR_LRL_RET(u,h−1)
    V′ ← {v ∈ V|[u,...,v] ∈ ROUTE(h−1)}
        %% V′ is set of reachable nodes in (h−1) hops from u
    V″ ← V′ ∪ {w ∈ V|(v,w) ∈ E for ∀v ∈ V′
        %% V″ is set of reachable nodes in h hops from u

    foreach v ∈ V″
        R ← {r ∈ ⋃_{0≤i<h} ROUTE(i)|r = [u;···;w] and (w,v) ∈ E}
        find  min_r ∈ R s.t. E_ret([min_r;v]) = min_{r∈R} E_ret([r;v])
        ROUTE(h) ← ROUTE(h) ∪ {[min_r;v]}
    end
```

Fig. 2. EAR-LRL algorithm based on typical energy model

Note that the complexity of EAR-LRL algorithm based on retransmission-aware energy model is $O(nh^2r)$ because it has to search one dimension more than that based on typical energy model. However, the energy gain is expected to be very small as long as p_l is sufficiently small value. We can use the algorithm based on typical model for the approximation of that based on retransmission-aware model with smaller computational complexity.

5 Performance Evaluation

We simulated the centralized EAR-LRL on typical energy model. Our simulator was developed on MATLAB 7.1. 200 nodes were deployed in 800 m × 800 m 2-D square. The communication range of each node is assumed to be 200 m. Mobility and fading effects other than path-loss were not considered. The routes were assumed to be built based on the location information of the participating nodes and all possible pair of source and destination nodes were equally measured.

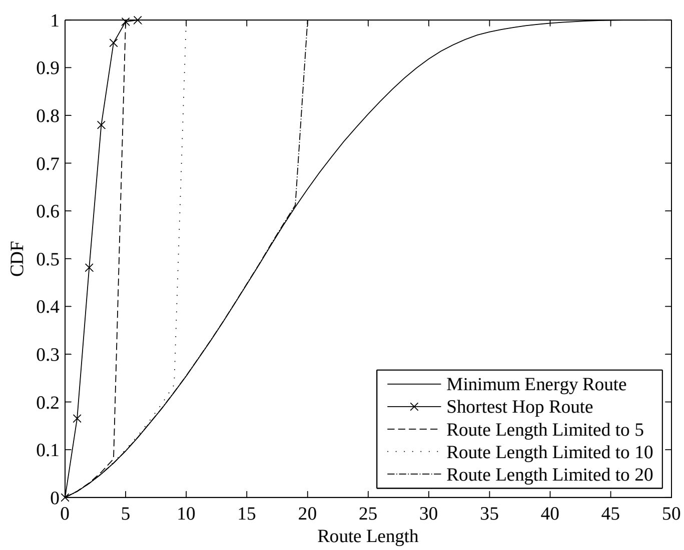

Fig. 3. The cdf of route length in terms of the route setup algorithms

As shown in Fig. 3, the minimum energy route lengths grow up to 48 hops in the simulation environment. However, routes built by EAR-LRL are shown to have strictly limited route. Our approach is expected to have good delay bound property for multimedia applications.

Fig. 4 presents the total energy consumed per route in communication with typical energy model when $\alpha = 1$ and $K = 4$. As shown, the route with limited route length of 20 is near optimal, even though its maximum route length is less than a half of that of minimum energy route. Moreover, the consumed energy with limited route length of 10 is also competent with significantly shorter route length.

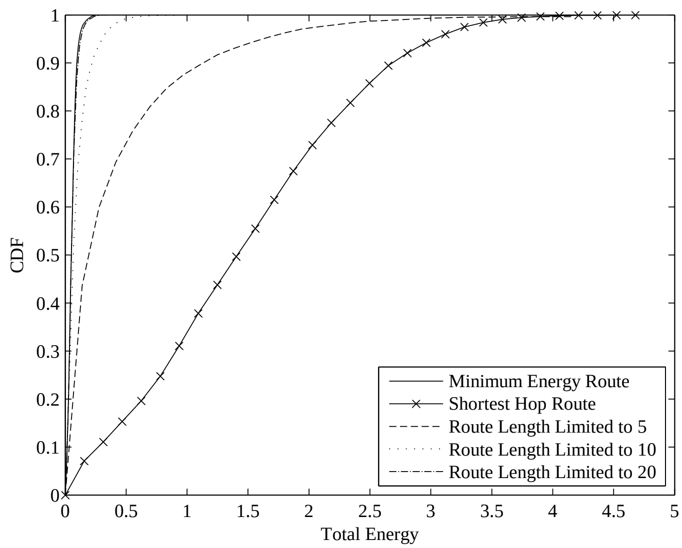

Fig. 4. The cdf of energy consumed in routing with typical energy model when $\alpha = 1$ and $K = 4$ in terms of the route setup algorithms

6 Concluding Remarks

We proposed the centralized EAR-LRL algorithms, which can be used for multimedia applications on ad hoc networks. They require small energy consumption and low latency together. Moreover, it can be used to build an energy-aware route based on retransmission-aware energy model, as well. The performance results show that EAR-LRL makes routes with fairly competitive energy costs and good delay characteristics.

The distributed version of EAR-LRL protocols can be developed based on the lemmas addressed in this work by each node managing total energy vector of routes with respect to the route length. In future, we plan to formalize distributed EAR-LRL protocols and evaluate them. Moreover, we will investigate the effect of mobility. We hopefully wish that the energy estimation on communication would help the accuracy of the energy cost estimation.

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