Batter-Aware Routing in Wireless Ad Hoc Networks – Part II: Battery-Aware Routing

Chi Ma 1 and Yuanyuan Yang 2

1 Department of Computer Science
State University of New York at Stony Brook, Stony Brook, NY 11790
dima@ics.sunysb.edu
2 Department of Electrical and Computer Engineering
State University of New York at Stony Brook, Stony Brook, NY 11790
yang@ece.sunysb.edu

Abstract. Energy efficiency is an important issue in ad hoc network routing. Battery technology cannot keep up with the increasing power demands from power-intensive applications on battery-powered wireless devices. Many power-aware routing protocols have been proposed to address this issue. These protocols assume the discharging of a battery is linear. However, as recent study in battery technology reveals, batteries tend to over consume power during discharging. If they do not have sufficient recovery, the over-consumed power will not be reimbursed. In order to achieve higher energy efficiency, battery behavior should be considered in the design of routing protocols. In Part I of this paper [1], we have introduced an on-line computable battery model, and shown that the model can accurately capture the behavior of the batteries used in wireless devices. This model does not require large lookup tables or complex computations and is suitable for implementation in wireless networks. In Part II of the paper, we first study the power dissipations in routing, and introduce a battery-aware power metric based on the on-line battery model proposed in Part I. We show that this metric can accurately model the energy consumption in ad hoc network routing. We then propose a battery-aware routing protocol (BAR) based on the power metric. The routing protocol is sensitive to the battery status of routing nodes and can avoid unnecessary energy loss in routing. We use the actual battery data from various mobile devices to evaluate the performance of the BAR protocol and compare it with existing protocols which are not battery-aware. Our simulation results show that the BAR protocol performs well and saves a significant amount of energy compared to existing routing protocols. The network lifetime and total data throughput are increased by up to 28% and 24%, respectively.

Keywords: Wireless ad hoc networks, energy efficiency, battery models, battery-awareness, routing protocols.

1 Introduction

In recent years, mobile ad hoc networks have played an increasingly important role in both military and civilian applications, such as video conference, emergency rescue and interactive games [5]. Ad hoc networks are composed of many mobile, self-organized and battery-powered
wireless devices. These wireless devices, such as PDAs, laptops and cell phones, adopt nickel-
cadmium or lithium-ion batteries as their power providers and tend to use up battery energy
in a short period [10, 11]. For example, today’s laptop can only last a few hours for work. The
growing interest of energy efficiency in ad hoc networks has resulted in very active research on
power-aware routing protocols for such dynamic and resource limited networks.

Many power-aware routing protocols have been proposed in the literature to enhance the
energy efficiency of ad hoc networks [5, 12]. They can be classified into two categories: topology-
based routing and position-based routing [5]. Topology-based routing protocols [2, 3], which are
originally used in wired networks, depend on the link information to make routing decisions.
However, the topology of an ad hoc network changes too frequently to be updated timely.
Maintaining a routing table at each node consumes a significant amount of energy in wireless
devices. To avoid maintaining routing tables, position-based routing protocols are proposed.
In general, this type of protocol can achieve high flexibility and low power dissipation [4]. In
position-based routing protocols, each node determines its own position using Global Positioning
System (GPS) [6]. The sender can forward packets based on only the location information of
the destination nodes and its one-hop neighbors. Depending on the way to choose the next hop
routing node, several different position-based protocols have been proposed. Most Forward within
Radius (MFR) [8] chooses the next routing hop farthest away within communication distance,
therefore to find a minimum hop-count routing path, while Nearest with Forward Progress (NFP)
[7] attempts to choose the nearest node as the next forwarding node to minimize the energy
required per routing task. The compass routing method, also referred to as DIR [9], aims to route
the packet to the neighbor with the closest angle to the destination, while Geographic Distance
Routing (GEDIR) protocol [9] selects a routing hop that is the closest to the destination, and
the routing path provided in this algorithm is loop-free.

However, previous position-based power-aware protocols are not aware of the status of bat-
teries. The power metric used in these protocols considers only the radiation dissipation of the
energy during routing. This is a rather rough metric and might not precisely model the power
dissipation in ad hoc networks. As discussed in Part I of this paper [1], battery tends to con-
sume more power when discharging, and reimburse the discharging loss later. A high discharging
loss indicates a “fatigue” battery. The discharging loss of a “fatigue” battery can be restored
if this battery has appropriate recovery, where “recovery” means the battery is disconnected
from its load. Hence, a more accurate power metric should take battery discharging loss into
consideration.

In Part II of this paper, we will first propose a new battery-aware power metric for energy
efficient routing in ad hoc networks. We will show that this metric can accurate model the power
dissipation of wireless devices. Then we introduce the concept of battery-aware routing based on
this power metric. In order to accurately calculate the battery discharging loss and its recovery,
we adopt the on-line computable battery model proposed in Part I of this paper [1]. The model
does not require large look-up tables or high computational complexity and is suitable for on-line
computation in routing protocols. We use the actual battery data from various mobile devices
to evaluate the performance of our protocol. In our simulations, we consider the number of
alive nodes, network lifetime, power dissipation and data throughput. Our simulation results
show that the battery-aware protocol performs well and can save a significant amount of energy
compared to existing routing protocols. The network lifetime and data throughput are also
increased.
2 Power Metric for Battery-Aware Energy Efficiency

In this section we introduce a power metric for battery-aware energy efficiency. There has been much work in the literature discussing the power metric for multi-hop wireless transmissions [5]. To transmit a packet from node a to node b in an ad hoc network, the energy consumption is usually modeled as

$$E = e + \gamma d_{(a,b)}^n$$ (1)

where $d_{(a,b)}$ is the distance between a and b, $n$ is the propagation loss coefficient, which is a constant determined by the communication environment, $\gamma d_{(a,b)}^n$ accounts for the radiated energy necessary to transmit over a distance of $d_{(a,b)}$, and $e$ is the energy utilized in the transceiver by digital processing and electronics.

However, the metric in (1) is rather rough for battery-powered devices. As discussed in Part I of this paper [1], batteries over consume power during discharging and can reimburse the over-consumed power if they have enough rest. The process of the reimbursement is referred to as battery recovery and the over-consumed power is referred to as discharging loss and is denoted by $\zeta$. To accurately model energy dissipation in battery-powered devices, $\zeta$ should be included in the power metric for multi-hop wireless transmissions. We therefore introduce a more accurate energy consumption metric that includes discharging loss $\zeta$:

$$E = e + \gamma d_{(a,b)}^n + \zeta$$ (2)

For the power dissipation of today's wireless devices, $\zeta$ is a significant amount of energy. We compare the battery performance of various widely used wireless devices in Table 1. Each device is assumed to be discharged at a current $I$ during its entire lifetime. $C$ is the total battery capacity and $\beta$ is the battery chemical parameter. We calculated the $\zeta$ using our on-line computable battery model introduced in [1] and evaluated the ratio of discharging loss $\zeta / C$ for each device. The higher the $\zeta / C$, the lower the energy efficiency it has. The results show that the battery discharging loss might be up to 30% of the total battery capacity.

**Table 1. Battery Performance of various Portable Devices**

<table>
<thead>
<tr>
<th>Device</th>
<th>$C$ (mAh)</th>
<th>$I$ (mA)</th>
<th>$\beta$</th>
<th>$\zeta$ (mAh)</th>
<th>$\zeta / C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Phone</td>
<td>72,000</td>
<td>400</td>
<td>0.5</td>
<td>5600</td>
<td>7.79%</td>
</tr>
<tr>
<td>mAh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tablet PC</td>
<td>100,000</td>
<td>2000</td>
<td>0.6</td>
<td>28000</td>
<td>28.00%</td>
</tr>
<tr>
<td>mAh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDA</td>
<td>120,000</td>
<td>1500</td>
<td>0.6</td>
<td>21000</td>
<td>17.50%</td>
</tr>
<tr>
<td>mAh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laptop</td>
<td>200,000</td>
<td>3500</td>
<td>0.5</td>
<td>49000</td>
<td>24.75%</td>
</tr>
<tr>
<td>mAh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We believe an energy-efficient routing protocol should be battery-aware. A node in the network should know its battery status in order to carefully schedule the battery activity and budget energy consumption. Based on our battery-aware power metric, next we will propose a battery-aware routing protocol (BAR). To further reduce the computational complexity for $\zeta$, in [1] we gave a simple way of using recovery length $\kappa$ to measure $\zeta$. Our BAR protocol will adopt this model to calculate $\kappa$ to capture the battery status.
3 Battery-Aware Routing Protocol

In this section we present a battery-aware routing (BAR) protocol based on our battery model. We assume that nodes are randomly deployed in an ad hoc network. Each node knows its geographic position. The node is powered by a battery with parameter $\beta$. We also assume that the source node transmits a stream of packets to the destination. This models the applications such as video conferences or multimedia transmissions where transmission is viewed as a stream. A node is called a routing node if it is on the routing path from the source to the destination. The time is divided into discrete time slots with fixed length $\delta$. In each time slot, a routing node can be assigned a task or idle. A task may be a routing activity, video displaying, software execution or any other power consuming function at this node. Multiple tasks may be assigned in the same slot. $I_n$ and $\kappa_n$ are the current and recovery length of the $n_{th}$ slot.

The BAR protocol is used to setup a routing path between a source and a destination. We first look at a simple example of battery-aware routing as shown in Fig. 1. In this ad hoc network, source node $S$ transmits packets to destination node $D$. The battery residual capacity $C$ and parameter $\beta$ are indicated in the figure. We compare the following two approaches.

![Battery-aware routing in an ad hoc network](image)

**Fig. 1.** Battery-aware routing in an ad hoc network. The current at each node is $I = 3.5A$. By switching between node $A$ and node $B$, the network achieves longer lifetime.

In the first approach, $S$ sends packets to $D$ through a multi-hop path $S \rightarrow A \rightarrow C \rightarrow F \rightarrow E \rightarrow D$. 45.35 minutes later, node $A$ uses up its energy. After that the routing path is changed to $S \rightarrow B \rightarrow C \rightarrow F \rightarrow E \rightarrow D$. The total connection lasts 90.7 minutes.

However, the lifetime can be extended in a simple way by switching between the above two paths. In the second approach, node $A$ and node $B$ alternate each other as the router. $A$ recovers its battery while $B$ is routing, and so on. This way the total lifetime is 113.15 min which is 24.8% longer than that of the first approach.

Our battery-aware energy efficient routing protocol is described in Table 2. In the protocol, a node needs to collect battery discharging loss status from all neighbors to find a next hop. In order to reduce the communication overhead, in turn to dissipate less power during routing path setup, BAR adopts $\kappa$ instead of $\zeta$ to measure the battery discharging loss. Because $\kappa$ is an integer and $\zeta$ is a floating number, adopting $\kappa$ can reduce the packet size as well as the computational complexity. The larger the recovery length $\kappa$, the higher the discharging loss $\zeta$, and the less the battery is recovered.

We introduce $\overline{R}$ and $\overline{C}$ to record battery status. $\overline{R}$ and $\overline{C}$ are the recovery status and the residual capacity in each time slot. Each routing node maintains these two vectors. Fig. 2 gives an example of $\overline{R}$ and $\overline{C}$ on a routing node. The battery is assigned 4 discharging tasks, each with a different recovery length $\kappa_1, \kappa_2, \ldots, \kappa_4$. The number of recovering tasks is summed into
**Table 2. Battery-Aware Routing (BAR) Protocol**

```plaintext
Receiver BAR procedure:
begin
  while power not used up do
    Update $\overline{R}$ and $\overline{C}$;
    Receive RTS from sender; Reply CTS with $\overline{R}$ and $\overline{C}$;
    Receive $\overline{R}'$ and $\overline{C}'$ from sender;
    $\overline{R} = \overline{R} + \overline{R}'$; $\overline{C} = \overline{C} - \overline{C}'$;
    Call {Sender BAR procedure}; // Selecting the receiver's next hop, and so on
  end while
end
Sender BAR procedure:
begin
  Hop Queue = $\{\}$: Broadcast RTS;
  Receive $\overline{R}_j, \overline{R}_{j+1}, \ldots, \overline{R}_n$, $\overline{C}_j, \overline{C}_{j+1}, \ldots, \overline{C}_n$ from $n_1$ neighboring nodes;
  for $j = 1, \ldots, n_1$ do
    if $\overline{C}_j - \overline{C}' > 0$ then
      if node $j$ is in forward direction then Hop Queue = Hop Queue $\cup \{j\}$;
      end if
    end if
  end for
  Call {BAR NextHopSelect procedure};
end
Send $\overline{R}'$ and $\overline{C}'$ to the selected nexthop;
BAR NextHopSelect procedure:
begin
  for each node $j$ in Hop Queue do nexthop = $j$ with min{$||\overline{R}_j + \overline{R}'||$};
    if the minimum is not unique then // Adopting different strategies:
      if under BAR-MFR algorithm then nexthop = $j$ with max{distance from $j$};
      if under BAR-NFR algorithm then nexthop = $j$ with min{distance from $j$};
      if under BAR-GEDIR algorithm then nexthop = $j$ with min{distance of $j$ and destination};
      if under BAR-DIR algorithm then nexthop = $j$ with min{angle of $j$ and destination};
    end if
  end for
end
```

$\overline{R}$. In Fig. 2, $\overline{R} = [0, 2, 3, 3, 2, 1]$. To calculate $\overline{C}$, we simply subtract battery capacity by the power dissipated in each slot. In this case it is $[500, 420, 375, 390, 405, 410](m\text{Ah}r)$.

The source also needs two vectors $\overline{R}'$ and $\overline{C}'$. $\overline{R}'$ and $\overline{C}'$ are the recovery vector and power needed for this transmission, respectively. For example, if a transmission takes $2\delta$ time, the recovery length $\kappa = 4$ and battery power consumption is $50m\text{Ah}r$ per time slot, then we have $\overline{R}' = [0, 1, 1, 1, 1, 0] + [0, 0, 1, 1, 1, 1] = [0, 1, 2, 2, 2, 1]$ and $\overline{C}' = [50, 50, 0, 0, 0, 0]$.

Along the routing path from the source to the destination, each hop is a sender and its next hop is the receiver. To select the next hop for a sender, BAR protocol is employed to select the most fully recovered node. On receiving a RTS (Request to Send) packet, available receivers reply a CTS (Clear to Send) packet. Their $\overline{R}$ and $\overline{C}$ are included in CTS. The sender receives CTS from all its $n_1$ one-hop neighbors. It selects the best available node by checking the following two rules for each node $j = 1, \ldots, n_1$: First, $\overline{C}_j - \overline{C}' > 0$ must be satisfied in order to make sure the next hop will not use up its battery during the transmission. Second, $\overline{R}_j + \overline{R}'$ is computed for each receiver, and the receiver with minimum recovery demand $\overline{R}_j + \overline{R}'$ is selected as the next hop.

Note that the minimal $\overline{R}_j + \overline{R}'$ may not be unique. When on a tie we can select the next hop by different strategies as shown in the description of the BAR protocol in Table 2. In
Task 4

Task 3

Task 2

Task 1

Time Slots:

\[ \kappa = 2 \]

\[ \kappa = 3 \]

Discharging Slot

Recovery Slot

Fig. 2. The battery status at a node. Current time is \( t_0 \). The battery is assigned four tasks. Recovery Vector is calculated by summing all recovering slots.

the NextHopSelect procedure, we use several existing routing algorithms: MFR, NFP, GEDIR and DIR, to show how BAR adopts existing routing strategies. These routing algorithms are commonly used in today’s wireless networks. As will be seen in our simulation results, BAR complements them and achieves better performance for multimedia transmissions. However, it should be pointed out that BAR is not restricted to these routing algorithms.

The communication complexity and time complexity of the BAR protocol depend linearly on the diameter of the network. Thus its complexity is \( O(\sqrt{n}) \), where \( n \) is the number of the nodes in the network.

The source node updates the routing path every \( t \) time, where \( t \) depends on the mobile speed of the nodes in the ad hoc network and is a multiple of \( \delta \). The higher the speed, the larger the \( t \).

Performance evaluations in Section 4 demonstrate that BAR protocol achieves good performance in prolonging network lifetime, increasing data throughput and reducing power dissipation.

4 Performance Evaluations

4.1 Simulation Setup

In this section we evaluate the performance of the BAR protocol in ad hoc networks and compare it with existing routing protocols: MFR, NFP, GEDIR and DIR. We consider the number of alive nodes, network lifetime, power dissipation and data throughput in the simulations. We assume that the ad hoc network is set up in a 150 \( \times \) 150 field, and wireless devices are randomly deployed in the field. Fig. 3 shows the network with 200 nodes distributed in it. The radius of each node is 15. These nodes are mobile. We assume that nodes move in a random direction at the speed of 0.1 per \( \text{min} \). The direction of moving is random. The length of a time slot \( \delta \) is set to 10\( \text{min} \). We randomly distributed 23 source-destination pairs in the area. Each source transmits packets to its corresponding destination, and updates its routing path every 30\( \text{min} \) (i.e., \( t = 30\text{\text{min}} \)). A transmission stops when there is no routing path setup between the source and its destination.

To model real-world applications, the nodes in this network are composed of several wireless portable devices: Cell phones, Laptops, PDAs and Tablet PCs. These data are collected from actual mobile devices. The profile of these devices is described in Table 3, where composition indicates the percentage of the corresponding device in the network. All these devices are randomly deployed.
4.2 Simulation Results

We implemented the BAR protocol in this network and compare its performance with aforementioned protocols separately. In our simulations the evaluated performance measures include the number of alive nodes, network lifetime, power dissipation and data throughput.

**Number of Alive Nodes:** We first evaluate the number of alive nodes during the network lifetime. Because BAR protocol enables nodes to use up battery power gradually, there should be more alive nodes compared with previous protocols. Fig. 4 shows that the number of the nodes in the network decreases as transmissions go on. We can see that since the battery-aware protocol is sensitive to battery status and carefully recovers node’s battery, the decreasing under BAR is slower than other existing protocols. Also note that the network lifetime is extended as well. In the simulations the lifetime can be prolonged by up to 28%.

**Network Lifetime:** In Fig. 4, we have seen that the network lifetime can be prolonged by BAR protocol. We evaluated the network lifetime under various network densities. In our simulation we setup networks with densities of 100, 150, 200, 250 and 300 nodes deployed in the $150 \times 150$ field. Fig. 5 shows the network lifetimes under different densities. We can see that battery-aware routing can greatly increase the network lifetime. Also note that the rate of lifetime increase is higher under a lower network density. For example, in the comparison between DIR and BAR-DIR, the lifetime can be increased by 44.4% under the density of 100 nodes, and increased by 13.8% under the density of 300 nodes. This is because that a network with lower density is more likely to have an insufficient number of nodes as routers to construct routing paths. The BAR protocol can carefully budget node power dissipation and preserve more alive nodes. Therefore, a lower density network benefits more from such battery power saving, and its rate of lifetime increase is higher than that of a higher density network.

**Power Dissipation:** Under previous routing protocols, a routing node tends to use up its battery power without recovery. Then the routing path is switched to another alive node. This will cause several problems. First, the residual battery power of each node is very different: Some nodes almost use up their power, while other nodes are left with full battery power. Second, the residual power at nodes is very low because discharging losses of batteries are not recovered.
Third, routing paths in the network tend to be re-set up more frequently, because a path has to be disconnected even if only a single router on it uses up its power. The operations of detecting disconnected paths and re-setting up a transmission consume a lot of extra power. As can be seen, under BAR protocol, the power consumed at nodes is more uniform: the residual power at each node is almost at the same level. We evaluated a network with 200 nodes. Fig. 6 shows the power distribution of the nodes under BAR protocol in the middle of network transmission (at the 200th min). The X and Y axes show the geographic positions of nodes in the network. The Z axis stands for the residual battery power of nodes. It can be seen that by adopting BAR, nodes can preserve higher battery energy. The simulation results show that the average battery power of a node can be increased by up to 45% compared with existing protocols. It can also be observed that the alive nodes are distributed more uniformly under BAR protocol.

Data Throughput: BAR protocol improves the data throughput as well. This is because that if routing nodes die and hence cannot setup routing paths between some source-destination pairs, the transmissions between these pairs of nodes have to be terminated. Therefore, previous protocols achieve less gross data throughput during the network lifetime. Fig. 7 compares the gross data throughput under different protocols. We can see that the improvement achieved by BAR protocol can be up to 24%.

5 Conclusions

In this paper, we have addressed the issue of achieving energy efficiency in ad hoc network routing by adopting a novel battery-aware energy model. The paper consists of two parts: energy model and battery-aware routing. In Part I, we proposed an on-line computable discrete time analytical model to mathematically model battery discharging behavior. The model does not require large look-up tables or high computational complexity, and is suitable for on-line battery capacity computation. In Part II, we presented a battery-aware protocol (BAR) to achieve energy efficiency in ad hoc network routing. The BAR protocol is sensitive to the battery status of routing nodes and can avoid unnecessary energy loss. We compare the BAR protocol with
previous protocols which are not battery-aware. Our simulation results show that the new routing protocol achieves much better performance than existing protocols.

Acknowledgements

This research was supported in part by NSF grant numbers CCR-0207999 and ECS-0427345 and ARO grant number W911NF-04-I-0439.

References

Fig. 6. The distribution of node power in the middle of network transmission under different protocols. Z is residual battery power at routing nodes.

Fig. 7. The gross data throughput of different protocols during their network lifetime.