J Comb Optim (2006) 11: 7–20
DOI 10.1007/s10878-006-5974-y

Energy conservation through resource-aware movement in heterogeneous mobile ad hoc networks

Wei Liu · Yanchao Zhang · Kejie Lu · Yuguang Fang

Accepted: October 25, 2005

Abstract Energy conservation in mobile ad hoc networks is of paramount importance because most mobile nodes usually have very limited energy supply. Previous research on this issue focused on the design at the network or MAC or physical layer. In this paper, we study this problem from the new perspective of node mobility, i.e., analyzing the impact of node movement on energy conservation. In particular, armed with the inherent resource heterogeneity in mobile ad hoc networks, we propose a novel resource-aware movement strategy to make better use of some powerful nodes to achieve energy conservation. We also formulate the resource-aware movement as a NP-complete distance-constrained least-cost (DCLC) routing problem and propose an efficient heuristic solution. Extensive simulations have been used to demonstrate the effectiveness of the proposed schemes.

Keywords Heterogeneous mobile ad hoc networks · Energy conservation · Resource-aware · Mobility · NP-Complete

1. Introduction

Mobile Ad Hoc Networks (MANETs), as one indispensable component to support future ubiquitous communications, have attracted considerable attention from both academia and industry. Nice features such as rapid deployment and self-organization without relying on any existing infrastructure make MANETs very attractive in both military and civil applications, where fixed infrastructures are unavailable or unreliable, yet fast network establishment and self-maintenance are a must. The realistic deployment of MANETs, however, faces

W. Liu (✉)· Y. Zhang · Y. Fang
Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611
e-mail: {liuw, yczhang}@ufl.edu; fang@ece.ufl.edu

K. Lu
Department of Electrical and Computer Engineering, University of Puerto Rico at Mayagüez, P.O. Box 9080, Mayagüez, Puerto Rico 00681
e-mail: lukejie@uprm.edu

many challenges stemming from their innate characteristics, such as time-varying and error-prone wireless links, limited bandwidth, node mobility and dynamic traffic patterns. Of particular interest to us are the issues arising from the energy constraints of mobile nodes. For instance, to support portability, most nodes are usually equipped with lightweight batteries with limited power and would become useless once depleted. Some adverse consequences of such node diminution include the degradation of network performance and unfavorable network partition. Thus, energy conservation, i.e., how to expend the energy resources in the network more frugally and evenly so as to prolong the network lifetime, becomes a crucial issue for MANETs. There has been a rich literature addressing the energy conservation issue in MANETs, ranging from power-saving mode (PSM) to transmission power control (TPC), and power-aware routing (PAM). Though these energy-aware MAC and routing protocols can in general help the whole system save the energy resources to some extent, there are still many other aspects one can explore to further improve the system-wide energy efficiency. As an example, similar to the traffic jam in daily life where vehicles flocks to a single spot, unwise movement may cause local traffic congestion, thus leading to unfavorable energy waste. This observation motivates us to address energy conservation from the perspective of node movement (Grossglauser and Tse, 2002; Chakraborty et al., 2003; Glodenberg et al., 2004; Zhao et al., 2004).

In addition to node movement, resource heterogeneity, as another inherent characteristic of MANETs, is often either overlooked or underutilized in designing energy conservation schemes for MANETs. While complicating the protocol design in MANETs, such heterogeneity also provides an opportunity to develop more efficient and effective energy conservation schemes. Though node heterogeneity can be interpreted in various ways, we limit the scope of this paper to heterogeneous networks in terms of energy supply. In such a network, most nodes (called R-nodes hereafter) are furnished with lightweight batteries with limited power, while others (called P-nodes hereafter) are powered by almost unlimited energy supplies such as energy-scavenging devices (e.g., solar cells) and dynamos when nodes are in some mobile vehicles. In a relative sense, the energy consumption of P-nodes can be considered as small or even negligible.

In this paper, we propose to address energy conservation by guiding nodes' movement and utilizing node heterogeneity. The basic idea is that, instead of moving in the field blindly in the network environment, e.g., always following the shortest-distance paths, nodes are instructed to travel much more intelligently by considering the system-wide objective of energy conservation and moving along the "resource-aware" paths in such a way that P-nodes can undertake as many communication tasks as possible so that less powerful R-nodes can save energy, thus leading to the elongation of the network lifetime.

The rest of the paper is organized as follows. We start with the formulation of the resource-aware movement problem in Section 2. In Section 3, we focus on the Waterhunter Movement problem and propose an efficient heuristic solution. Section 4 evaluates the performance of the proposed schemes. Finally, this paper is concluded in Section 5.

2. Problem formulation

We consider a MANET consisting of tens or even hundreds of mobile nodes, among which there are N_r regular battery-powered nodes (R-nodes) and N_p powerful nodes (P-nodes) with almost unlimited energy supplies such as solar cells. Communication devices installed on a mobile vehicle and powered by inside alternators are other examples of such P-nodes. Usually, N_p is much smaller than N_r. We assume that all the nodes are able to generate traffic or forward packets for others no matter when they are at rest or in motion. Intuitively, since P-nodes have relatively infinite energy reservoir as opposed to battery-powered R-nodes, they should be utilized as much as possible to save the scarce resources of R-nodes and thus prolong the whole network lifetime. For example, a packet should be forwarded to a P-node whenever possible if energy savings can be expected. On the other hand, we should reduce the use of R-nodes if we cannot completely avoid using them. How to realize this simple rationale, however, is by no means an easy task.

In what follows, we first present a general mobility model that is used to characterize nodes' movement patterns. We then introduce the resource-aware movement problem in its general form with the consumption of energy resources as the sole optimization objective.

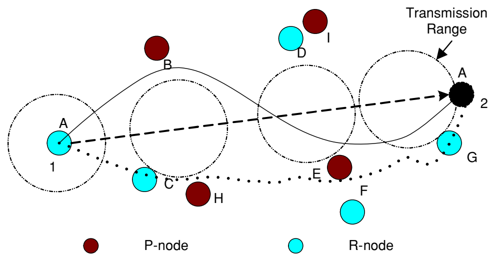
2.1. General mobility model (GMM)

During an observation period T, we assume that there are some designated locations that any node i, be it a P-node or R-node, should stop by at some designated time instances. For example, a student carrying a mobile device may appear in the classroom during school time while in the cafeteria during lunchtime. Let J_i denote the size of the ordered list of locations node i should visit during T, which might be different for each individual node. We denote by $pos_i(j)$ $(0 \leq j < J_i)$ the jth location that node i should stop by and by $t_i(j)$ the required time instance. Then $\mathrm{pos}_i(0)$ denotes the starting point of node i, and $\mathrm{pos}_i(J_i - 1)$ denotes the location of its last stop during T. We will also call as an *epoch* (Johnson and Maltz, 1996) the time duration from one node leaving the current stop until it reaches the next stop henceforth. Whenever arriving at some designated location at the specified instance, each node is assumed to pause for a while according to concrete application requirements. Let $\mathrm{pause}_i(j)$ indicate the time node i spends at $\mathrm{pos}_i(j)$.

Based on the above definitions, the order list $\{\mathrm{pos}_i(j), t_i(j), \mathrm{pause}_i(j), 0 \leq j < J_i\}$ can well characterize the itinerary of node i during the observation period T. Let $\overbrace{\mathrm{pos}_i(j)\mathrm{pos}_i(j+1)}$ denote the path travelled by node i from its jth stop to the $(j+1)$th stop. Provided that each node travels at a constant speed between two consecutive stops, the travelling speed of node i from $\mathrm{pos}_i(j)$ to $\mathrm{pos}_i(j+1)$ is given by $\frac{\mathrm{length}(\overbrace{\mathrm{pos}_i(j)\mathrm{pos}_i(j+1)})}{t_i(j+1)-t_i(j)-\mathrm{pause}_i(j)}$. Notice that node i can follow potentially many different paths, e.g., a straight path or a zigzag path or even a tortuous path, as long as the time constraint is satisfied, that is, it can reach $\mathrm{pos}_i(j+1)$ at the time instant $t_i(j)$. However, once the path between two consecutive stops is determined, the velocity of the node between these two stops is determined and fixed. Therefore, once the paths between all pairs of consecutive stops are determined, the movement pattern of a node during T is also determined.

The general mobility model (GMM) described above bears both similarities and differences with the random waypoint model (RWM), the most commonly-used mobility model in simulating MANET protocols (Johnson and Maltz, 1996; Yoon et al., 2003). Both models are characterized by a collection of locations of next stops, travelling speeds, and travelling time. Different from GMM, RWM requires a node to first choose the location of its next stop and the travelling speed, which leads to the determination of the travelling time. Our GMM actually does the opposite by first determining the next visited location and the travelling time so as to determine the travelling speed. The biggest difference, however, is that, in RWM nodes always travel along the straight paths connecting two consecutive stops, while in GMM, nodes can travel along arbitrary paths as long as they do not violate the time requirements, i.e., they should arrive at the designated stops at the specified time instances.

Fig. 1 Multiple paths between two consecutive stops



2.2. Resource-aware movement

As mentioned before, in the general mobility model there might be potentially many different paths between any two consecutive stops. Define PATH($\text{pos}_i(0), \text{pos}_i(J_1 - 1)$) as node i's path set which is the concatenation of all the paths $\overbrace{\text{pos}_i(j)\text{pos}_i(j+1)}$. In this paper, we are interested in finding the optimal path sets for all the nodes such that the total energy consumption for communications by all the nodes during the observation period T is minimized (the objective function), while all the ordered lists of visited locations and the corresponding time instances should not be violated (the constraints). To help better understand the importance of this problem, we utilize the movement of a single node between two consecutive stops as an example. As shown in fig. 1, suppose an R-node A should move from the current location 1 to the next location 2. It can choose the shortest straight path (the dashed one) as it does in the random waypoint model. However, considering that node A may forward or generate packets destined for other nodes during the movement process, the shortest straight path is not necessarily the best one for achieving the system-wide energy efficiency. Instead, the dotted and solid paths are much better candidates through which node A can take advantage of more P-nodes by forwarding to the encountered P-nodes the packets destined for other nodes and letting them finish the rest of the task. Due to this reason, we call this problem the *resource-aware movement* problem in that nodes now are moving with the system-wide resource (energy) consumption in mind instead of moving blindly as before.

The general resource-aware movement problem itself is far too complicated to be solvable. To render it tractable, we make some approximation and decouple it into two relatively simpler subproblems: the Waterhunter Movement problem and the Firehunter Movement problem. In the former, we assume that only R-nodes are capable of moving and all the P-nodes are stationary whose locations are known *a priori* to R-nodes. By contrast, in the latter, we assume that all the R-nodes are stationary and only P-nodes are able to move.

- *Waterhunter Movement*: In the network with N_p stationary P-nodes and N_r mobile R-nodes, given all the order lists of $\{\text{pos}_i(j), t_i(j), \text{pause}_i(j), 0 \leq j < J_i\}$, the Waterhunter Movement Problem[1] is to determine the optimal travelling path set for each R-node such that the total energy consumption of the whole network during T is minimized.
- *Firehunter Movement*: In the network with N_p mobile P-nodes and N_r stationary R-nodes, given all the order lists of $\{\text{pos}_i(j), t_i(j), \text{pause}_i(j), 0 \leq j < J_i\}$, the Firehunter

[1] If we compare energy resources to "water", the movement of R-nodes is similar to the behavior of waterhunters who are always looking for "fountains" (P-nodes), hence the name.

Movement Problem[2] is to determine the optimal travelling path set for each P-node such that the total energy consumption of the whole network during T is minimized.

Both problems are interesting and worthy of rigorous study. In this paper, we focus on finding a nearly optimal solution to the Waterhunter Movement problem.

3. Waterhunter movement

3.1. Simplified waterhunter movement problem

In the Waterhunter Movement problem, we assume that all the N_p nodes are stationary during the observation period T and are willing to forward packets for other less powerful R-nodes. For simplicity, we do not dwell on how to place P-nodes to attain the optimal system performance, which is believed to be a challenging problem itself and is currently under investigation. Instead, we assume that each R-node knows the locations of all the P-nodes and its own location at any time, and can as well adjust its moving direction at will. For the time being, we assume here that all the P-nodes and R-nodes have the same transmission range *TR*. We will discuss the case that P-nodes have greater transmission range than R-nodes in Section 3.3. It is worth pointing out that the findings in this paper can be easily extended to the case that each node has individual transmission range.

The original Waterhunter Movement problem aims at minimizing the total energy consumption of the whole network during the observation period T, which is a global optimization problem and still too hard to be solvable. To make it tractable, we have to make some approximations to get a suboptimal solution. We assume that an R-node moves at a constant speed in one epoch, i.e., between two consecutive stops, and the maximum speed it can take is a system-wide value $speed_{\max}$. Therefore, the longest path node i can travel in one epoch is $l_{\max} = \mathrm{speed}_{\max} \times (t_i(j+1) - t_i(j) - \mathrm{pause}_i(j))$. To achieve the system-wide goal of energy conservation, instead of moving along the straight path connecting two consecutive stops $\mathrm{pos}_i(j)$ and $\mathrm{pos}_i(j+1)$, node i may travel along a resource-aware path with the purpose of letting the encountered P-nodes forward on behalf of it as many as possible packets destined for other nodes. For simplicity, we assume that when moving towards a P-node, node i always goes along the straight path connecting the destined P-node and itself. Therefore, $\overbrace{\mathrm{pos}_i(j)\mathrm{pos}_i(j+1)}$ is a set of zigzag straight paths if there exist multiple P-nodes. Notice that the simplified target now is to find an optimal path set for each individual node to minimize its total energy consumption during the observation period T instead of that of the whole network. We intend to utilize the solutions to this localized optimization problem to approximate the original global optimization problem, which is believed to be too complicated to be tractable.

Normally, when moving between two consecutive stops $\mathrm{pos}_i(j)$ and $\mathrm{pos}_i(j+1)$, node i may have several potential P-nodes to utilize. It is, however, usually unwise for node i to pass by each of them. The reason is that, the longer path node i takes, the faster speed it should move at, as described in the aforementioned general mobility model. It is well-known that a faster movement speed may cause undesirable problems such as the instability of routing paths and the drop of packets. Therefore, some rules should be designed to guide each R-node in deciding which P-nodes and in what order it should pass through between two consecutive

[2] If we compare energy resources to "water", the movement of P-nodes is similar to the behavior of fire-hunters who are always looking for places "on fire" or "lack of water" (R-nodes), hence the name.

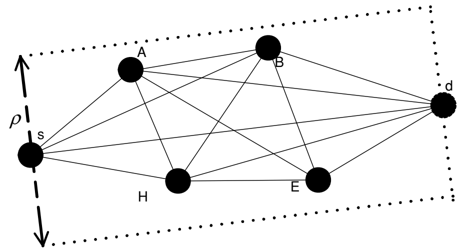


Fig. 2 An exemplary complete graph

stops. A simple rule would be to only consider as candidates the P-nodes whose distance from the direct link between any two consecutive steps are no more than a threshold ρ. For example, ρ can equal $1.5 \times TR$, where TR is the transmission range of each node.

With node i as an example, we can put the simplified Waterhunter Movement problem in another way: given a source (i's current stop), a destination (i's next stop), and some available intermediate P-nodes, and the path length constraint l_{max}, find a path as energy-efficient as possible from the source to the destination, which is might be either the direct link connecting the source and destination or a zigzag path through multiple P-nodes. Figure 2 depicts such a topology, where a rectangular area, called the *ρ-bounded rectangular area* hereafter, is formed such that only the P-nodes residing in this area are considered as valid candidates. In addition, each link is of the forward direction from the source s to the destination d simply because travelling backward is energy inefficient. We assign to each link two weights, of which one represents the physical distance between two ends of a link and the other indicates the virtual energy cost (defined shortly) incurred by choosing this link. The simplified Waterhunter Movement problem can be boiled down to a distance-constrained least-cost (DCLC) (Reeves and Salama, 2000) routing problem which is formally defined as follows.

Consider a directed network that can be modelled as a complete graph $G = (V, E)$, where V is the set of vertices consisting of the source, the destination, and all the valid candidate P-nodes, and E is the set of edges connecting each pair of nodes. V can be further divided into two subsets, namely, $\mathcal{U}$ including the source s and destination d, and $\mathcal{P}$ containing all the P-nodes. In addition, each edge $e \in E$ represents the movement from the tail node to the head node. Let $\mathbb{R}^+$ denote the set of non-negative real numbers. Each edge $e \in E$ is associated with two non-negative functions: a distance function $dist(e) : E \to \mathbb{R}^+$ representing the physical distance between the end nodes of e and an energy cost function $cost(e) : E \to \mathbb{R}^+ \bigcup\{0\}$. More specifically, for a given edge $e(v_i, v_j)$, its energy cost is defined as

$$\text{cost}(e(v_i, v_j)) = \begin{cases} f(\text{dist}(v_i, v_j)) + g(\text{dist}(v_i, v_j)) & v_i = s, v_j = d \\ f(\text{dist}(v_i, v_j)) + g(\text{dist}(v_i, v_j) - TR) & v_i = s, v_j \in \mathcal{P} \\ & \text{or } v_j = d, v_i \in \mathcal{P} \\ f(\text{dist}(v_i, v_j)) + g(\text{dist}(v_i, v_j) - 2 \times TR) & v_i, v_j \in \mathcal{P}. \end{cases}$$

Here f is the cost, such as gas, fuel or other types of resources, required for the mechanical movement[3]; g is used to reflect the cost for communications. g can be any non-decreasing

[3] In this paper, for simplicity, we assume that people on foot carry the communication devices and we do not take the cost for the mechanical movement into account, that is, $f(\cdot) = 0$.

function in distance that converts a given distance value into a non-negative cost, for example,

$$g(x) = \begin{cases} x & x > 0 \\ 0 & x \leq 0. \end{cases}$$

The motivation for the above definition of the edge energy cost is as follows. Whenever a R-node moves into the transmission range *TR* of a P-node, it is capable of forwarding to the P-node packets destined for other nodes so as to conserve energy. At one extreme, if a R-node moves along an edge not (partially) covered by any P-node, all the packets from this R-node would be forwarded to other energy-constrained R-nodes, which is the most unfavorable situation. At the other extreme, if a R-node moves along an edge completely covered by one or several P-nodes, all the packets from this node could be forwarded to the P-node(s), which is the most desirable situation. Notice that the energy cost function given above can well capture this effect. Though there might exist other meaningful metrics, we believe the chosen one is very simple and useful.

We also define the non-negative delay and cost functions for any path p as

$$dist(p) = \sum_{e \in p} dist(e)$$

and

$$cost(p) = \sum_{e \in p} cost(e).$$

Given the above definitions, the DCLC routing problem is to find a path p from s to d such that $\min\{\text{cost}(p), p \in P_d\}$ is achieved, where P_d is the set of all feasible paths from s to d satisfying the distance constraint $l_{\max}$, i.e., $\text{dist}(p) \leq l_{\max}$. Moreover, we define $P_{ld}(s, d)$ as the path with the least distance from s to d, and $P_{lc}(s, d)$ as the path with the least cost from s to d. Apparently, with the above definition of dist(e), $P_{ld}(s, d)$ is the straight path directly connecting s and d.

It has been shown in Garey and Johnson (1979) that the DCLC routing problem is NP-complete even for undirected networks. In the following section we will propose an efficient heuristic algorithm to provide a suboptimal solution to this DCLC problem and hence to the original Waterhunter Movement problem.

3.2. RAM-DCLC algorithm

As mentioned before, we assume that a R-node, say i, is aware of its own itinerary $\{\text{pos}_i(j), t_i(j), \text{pause}_i(j), 0 \leq j < J_i\}$ and the locations of all the P-nodes during the observation period T. The procedure of node i's resource-aware movement from the current location $\text{pos}_i(j)$ to the next location $\text{pos}_i(j)$ is summarized in Table 1. Node i first needs to determine the candidate P-nodes in the *ρ-bounded rectangular area* and then constructs a complete graph like the one in fig. 2, consisting of the vertices s (a virtual node at $\text{pos}_i(j)$), d (a virtual node at $\text{pos}_i(j+1)$), and all the found candidate P-nodes. It then proceeds to calculate the distance and the energy cost for each link and finally generates the weighted graph G. The next step is to call the process *RAM-DCLC* given in Table 2to get the DCLC path P_{dclc} whose length is bounded by $l_{\max} = \text{speed}_{\max} \times (t_i(j+1) - t_i(j) - \text{pause}_i(j))$. It then moves towards $\text{pos}_i(j+1)$ at a constant speed of $\text{speed}_{\text{dclc}} = \frac{\text{dist}(P_{\text{dclc}})}{t(i,j+1) - t(i,j) - \text{pause}(i,j)}$ along the found P_{dclc}. Upon reaching $\text{pos}_i(j+1)$, node i pauses for a period $pause_i(j+1)$.

Table 1 RAM: Resource aware movement

1. Determine the candidate P-node set *CHS* in the *ρ-bounded rectangular area*;
2. Construct a complete graph G with virtual nodes s and d, and all the nodes in *CHS*;
3. Label each link e in G with cost(e) and dist(e);
4. Find the DCLC path P_{dclc} by calling RAM-DCLC(G, s, t, $l_{\max}$);
5. Determine the traveling speed along P_{dclc} as $\text{speed}_{\text{dclc}} = \frac{\text{dist}(P_{\text{dclc}})}{t(i,j+1)-t(i,j)-\text{pause}(i,j)}$;
6. Move along P_{dclc} at a speed of $\text{speed}_{\text{dclc}}$;

Table 2 *RAM-DCLC*: A DCLC routing algorithm for the Waterhunter Movement

```
For each node v_k in G, find the P_lc(v_k, d) and P_ld(v_k, d) and
  their respective next hops nid(P_lc(v_k, d)) and nid(P_ld(v_k, d));
distSoFar = 0; P_dclc = s; ThisNode = s;
while (ThisNode ≠ d) do
    if ((dist(P_lc(ThisNode, d)) + distSoFar) ≤ l_max) then
        v = nid(P_lc(ThisNode, d));
        distSoFar = distSoFar + dist(ThisNode, v);
        P_dclc = P_dclc + {v};
        ThisNode = v;
    else
        for each neighboring node w ∉ P_dclc do
            calculate weight(ThisNode, w);
        end for
        v = extract(ThisNode);
        distSoFar = distSoFar + dist(ThisNode, v);
        P_dclc = P_dclc + {v};
        ThisNode = v;
    end if
end while
Return P_dclc
```

Following the previous process, it can then move towards the next stop $\text{pause}_i(j+2)$ until all the required stops $\{\text{pos}_i(j), 0 \le j < J_i\}$ during the observation period T are visited.

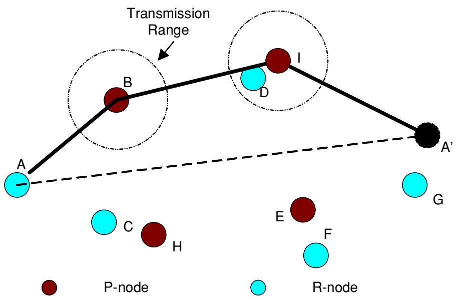
The proposed DCLC algorithm *RAM-DCLC* is summarized in Table 2, in which the *weight*() function is defined as follows:

$$\text{weight}(v_i, v_j) = \begin{cases} cost(v_i, v_j) + cost'(v_j, d) & cond(1) \\ +\infty & o.w., \end{cases}$$

and

$$\text{cost}'(v_i, d) = \begin{cases} \text{cost}(P_{lc}(v_i, d)) & \text{cond}(2) \\ \text{cost}(P_{ld}(v_i, d)) & o.w., \end{cases}$$

Fig. 3 An exemplary resource-aware movement



where

$$cond(1) = distSoFar + dist(v_i, v_j) + dist(P_{ld}(v_i, d)) \leq l_{\max}$$

and

$$\text{cond}(2) = \text{dist}SoFar + \text{dist}(v_i, v_j) + \text{dist}(P_{lc}(v_i, d)) \leq l_{\max.}$$

The function *extract*() is used to choose the node, say w, whose *weight*(v_i, w) is the minimum one among all the neighboring nodes of *ThisNode*. If more than one node have the same minimum value, it chooses the one with the smallest $\text{dist}SoFar + \text{dist}(v_i, v_j) + \text{dist}(P_{ld}(v_j, d))$.

In the *RAM-DCLC* algorithm, for each node v_k in G, the Bellman-Ford or Dijkstra shortest-path algorithm can be used to find the $P_{lc}(v_k, d)$ and $P_{ld}(v_k, d)$ and their respective next hops *nid*$(P_{lc}(v_k, d))$ and $\text{nid}(P_{ld}(v_k, d))$. Since the optimization objective is the path cost, at each intermediate node v, *RAM-DCLC* always chooses the next hop w with minimum $\text{cost}(v, w) + \text{cost}'(w, d)$ while not violating the distance constraint $l_{\max}$. *RAM-DCLC* is able to find a feasible path satisfying the distance constant while keeping the path cost as small as possible. In particular, we have the following theorems for this algorithm.[4]

Theorem 1. *RAM-DCLC can always find a feasible path from a source s to a destination d satisfying the given distance constraint $l_{\max}$ if such feasible paths exist.*

Theorem 2. *The path found by* RAM-DCLC *is loop-free.*

Theorem 3. RAM-DCLC *always terminates in finite time.*

Now we utilize the example given in fig. 3 to illustrate the resource-aware movement process using the proposed *RAM-DCLC* algorithm. Suppose node A intends to move from its current location to the location where A' resides according to its itinerary. In this example ρ is set to $1.5 \times TR$ so that there are four candidate P-nodes. Based on the output of *RAM-DCLC*, node A should move along the DCLC path denoted by the solid line instead of the straight path denoted by the dash line. In this way, energy savings can be expected by forwarding to the two P-nodes the packets it carries for other nodes and letting the P-nodes finish the rest transmissions (either single-hop or multi-hop) on behalf of this node.

Figure 4 compares a R-node's resource-aware movement trail and its random waypoint movement trail with 8 P-nodes in a $1500 \times 300\,\text{m}^2$ field. The data used were generated using

[4] The correctness of these theorems can be justified following the proof in Liu et al. (2005).

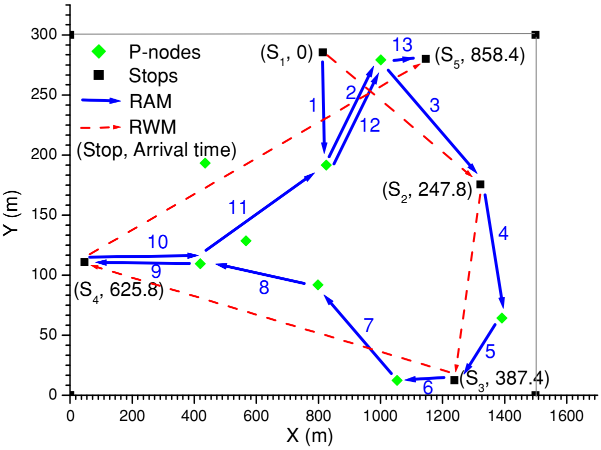


Fig. 4 Resource-aware movement (RAM) vs. random waypoint movement. A R-node should consecutively visit $S_1 - S_2 - S_3 - S_4 - S_5$ and the solid lines are labeled by the sequences they were passed through

OPNET and the pause time of the R-node was 120 s. In addition, the transmission range of each node was set to 250 m. It is clear that our proposed resource-aware movement strategy enables the R-node to have more opportunities of approaching and utilizing the P-nodes as compared to the random waypoint movement.

3.3. Incorporate RAM into DELAR

In our previous discussion, we assume that P-nodes have the same transmission range TR as R-nodes. However, in more practical heterogeneous MANETs, P-nodes may have greater transmission capabilities than the R-nodes. To make use of such powerful P-nodes especially when P-nodes can adjust their transmission power to cover a larger range than R-nodes, in our previous work (Liu et al., 2004), we proposed an energy efficient relaying framework DELAR to efficiently utilize P-nodes to conserve energy. DELAR is a joint design of scheduling, routing and power control. In this framework, we proposed an Asymmetric MAC (A-MAC) to enable reliable transmissions over unidirectional links caused by the asymmetrical transmission power between P-nodes and R-nodes. Since RAM and DELAR utilize powerful nodes to conserve energy from totally orthogonal perspectives, RAM can be directly incorporated into the DELAR framework. As we will see shortly, with the help of DELAR, RAM can further improves the energy efficiency when P-nodes and R-nodes have different transmission capabilities. In addition, to further improve the energy efficiency, P-nodes assume shorter delays than R-nodes for routing packets so that P-nodes can have much more chances to be chosen on the routes and can forward packets for R-nodes.

4. Performance evaluation

4.1. Simulation setup

We implemented the resource-aware mobility model and DELAR (Liu et al., 2004) in OPNET.

We simulated a network with N_r R-nodes and N_p P-nodes in a 1500×300 field, where $N_r = 46$ and $N_p = 4$. All the R-nodes were capable of moving in the field, while all the P-nodes were fixed. Though a careful deployment of P-nodes may improve the system performance (Ye et al., 2003), we simulated a worse scenario that the P-nodes were randomly

Table 3 Energy parameters

Symbol	Value	Unit
m_{send}	1.89	uW-sec/byte
b_{send}	246	uW-sec
m_{recv}	0.49	uW-sec/byte
b_{recv}	56.1	uW-sec
b_{sendctl}	120	uW-sec
b_{recvctl}	29	uW-sec

deployed in the field. The transmission range of the R-nodes was 250 m. For the P-nodes, we simulated two cases in which the P-nodes had the transmission ranges 250 m and 500 m, respectively.

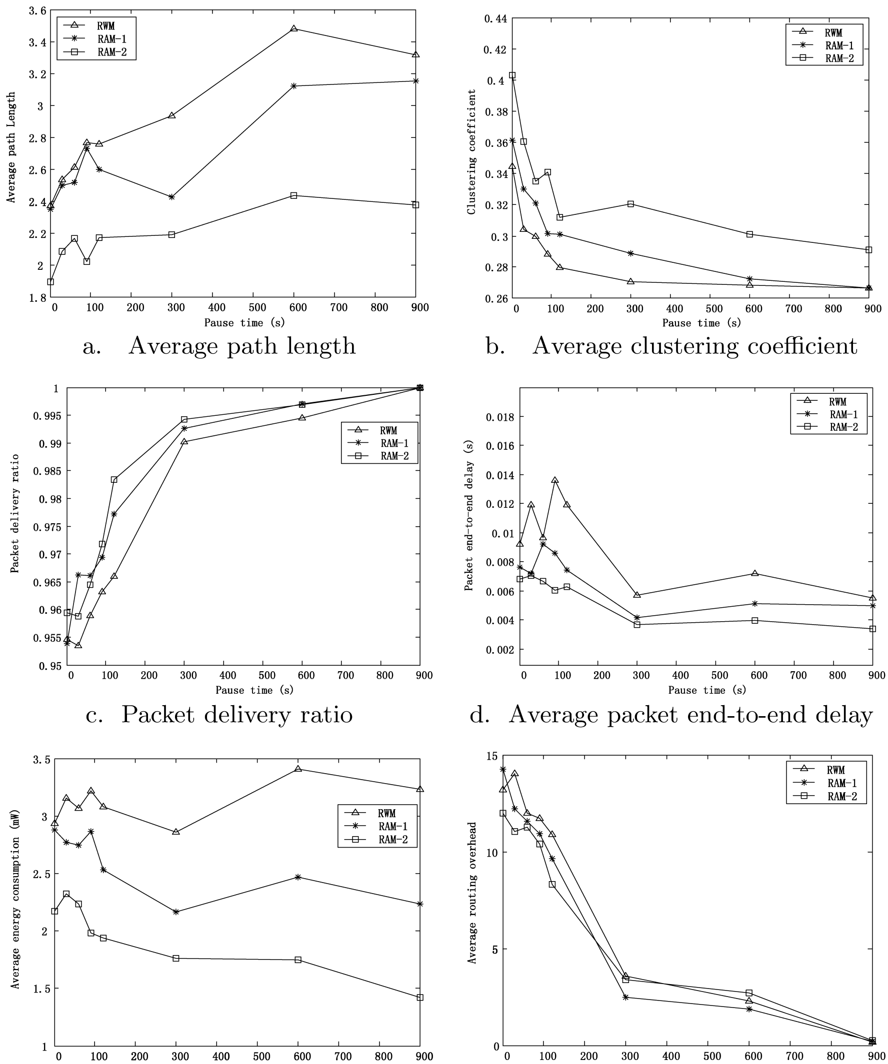
The energy consumption for the R-nodes followed the linear energy model proposed in Feeney and Nilsson (2001): energy $= m \times$ length $+ b$, where m is an incremental cost of each operation, b is the fixed cost of each operation, and length is the size of the frame sent/received.[5] The (m, b) values provided in Feeney and Nilsson (2001) were summarized in Table 3 and used in all the calculations of this paper.

We intended to compare the proposed resource-aware mobility model (denoted by RAM) with the modified random waypoint model (denoted by RWM) presented in Yoon et al. (2003), which can guarantee the convergence of average nodal speed throughout the simulation time. For this purpose, we first ran the simulations using RWM and recorded the stops, the starting/arrival time instances, the moving directions, and the movement speeds of all the movement epochs. We then used this movement profile to generate the itinerary $\{\text{pos}_i(j), t_i(j), \text{pause}_i(j), 0 \le j < J_i\}$ for each node such that in both models each node would drop by the same stops at the same time instances, but may follow totally different movement trails and take different movement speeds. Both models had the same maximum speed 20 m/s and we adjusted nodal pause time to vary the network mobility. The traffic used were 20 CBR connections with randomly selected source-destination pairs. All the data packets were 64 bytes and were sent a speed of 4 packets/second. Each simulation was executed for 15 simulated minutes and each data point represents an average of ten runs with identical traffic models, but differently generated mobility scenarios.

4.2. Simulation results

We compared RAM with RWM in terms of the commonly used metrics including packet delivery ratio, average packet end-to-end delay, average packet energy consumption, and average routing overhead. Motivated by the small-world phenomenon (Albert and Barabsi, 2002), we used two additional metrics, average path length and average clustering coefficient, which are two defining characteristics of small-world networks. The former means the average number of hops a packet may travel through, while the latter indicates the connectivity of an average neighborhood in the network, defined as the average node degree divided by the network size (Albert and Barabsi, 2002). The simulation results are presented in fig. 5, where RAM-1 indicates the case that the P-nodes and R-nodes have the same transmission

[5] For the A-MAC control frames P-RTS/P-CTS/P-ACK, the fixed costs $b_{sendctl}$ and $b_{recvctl}$ were used because they have the similar size



a. Average path length
b. Average clustering coefficient
c. Packet delivery ratio
d. Average packet end-to-end delay
e. Average energy consumption
f. overhead

Fig. 5 Simulation results

range 250 m and RAM-2 denotes the case that the P-nodes have a larger transmission range 500 m.

Figure 5(a) and (b) compare RAM and RWM with regard to average path length and average clustering coefficient, respectively. We can see that RAM can shorten the average path length and increase the clustering coefficient as compared to RWM. That is because in RAM the R-nodes are always trying to move towards some P-nodes between two consecutive stops. Such behaviors would effectively bring more R-nodes to the vicinity of P-nodes, leading to shorter paths and larger clustering coefficients. In some sense, such resource-aware movement creates a "small-world" network, which results in some performance gains shown below. In addition, since the P-nodes in RAM-2 have a larger transmission range and thus have more neighbors that those in RAM-1, we can observe that RAM-2 further reduces the average path length and increases the average clustering coefficient.

Figure 5(c) compares the average packet delivery ratios of RAM and RWM, which is defined as the ratio of delivered data packets to those generated by the sources. As we can see, the PDR of RAM-1 or RAM-2 is always higher than that of RWM. This result is of no surprise since the shorter average path length implies the network-wide less traffic load and less packet drops due to the MAC-layer contention and channel errors, all of which would contribute to the increase of the PDR. Due to the same reason, RAM-2 demonstrates a higher PDR than RAM-1.

Figure 5(d) depicts the comparison of average end-to-end packet delay, defined as the time duration from when a packet is generated till it is received by the destination. The shown advantage of RAM over RWM mainly results from the aforementioned shorter average path length and higher clustering coefficient. Again, RAM-2 outperforms RAM-1 in reducing average packet delay because of the shorter average path length.

Figure 5(e) shows average energy consumption, defined as the total energy consumption for transmitting and receiving all data and routing packets divided by the number of delivered packets. Apparently, our RAM can conserve a significant amount of energy as compared to RWM because the R-nodes are always moving along the paths through which the P-nodes can be utilized as much as possible. Since the P-nodes in RAM-2 have a larger transmission range, statically less R-nodes are involved in packet transmissions and thus RAM-2 can help the system conserve more energy than RAM-1.

Figure 5(f) demonstrates average routing overhead, defined as the average number of routing packets involved in delivering 100 data packets. As we can see, our RAM has smaller routing overhead than RWM. That is because in RAM packets can be forwarded to their destinations through shorter paths in shorter time, thus fewer routing errors occur.

To summarize, the proposed resource-aware movement strategy has many significant and positive impacts on the system performance. It makes the network more like a "small-world" network with shorter average path length and higher clustering coefficient. This results in improved packet delivery ratio, shortened end-to-end delays, and most importantly, much better energy conservation. Therefore, the combination of node mobility and heterogeneity is a valid means to address the energy conservation issue in MANETs. The results also suggest that making the network a small-world network may have a lot of positive effects on the system performance and it deserves further investigation.

5. Conclusion

In this paper, we studied the energy conservation problem from the new perspective of node mobility, i.e., analyzing the impact of node movement on the system-wide energy conservation. We proposed a novel resource-aware movement strategy to take full advantage of some powerful nodes in heterogeneous mobile ad hoc networks. We then formulated the resource-aware movement as a NP-complete distance-constrained least-cost (DCLC) routing problem and proposed an efficient heuristic solution. In addition, the proposed resource aware movement strategy can be incorporated into other energy conservation schemes, e.g., DELAR, to further improve the energy efficiency. We used extensive simulations to show the effectiveness of the proposed scheme.

In our future work, we will study the Firehunter Movement problem (cf. Section 2.2) and strive to propose a unified solution for the general resource-aware movement problem.

Acknowledgments This work was supported in part by the U.S. Office of Naval Research under grant N000140210464 (Young Investigator Award), and the U.S. National Science Foundation under grant ANI-0093241 (CAREER Award) and under grant DBI-0529012.

References

Albert R, Barabsi A.-L (2002) Statisctical mechanics of somplex networks. Review of Modern Physics 47–97.

Chakraborty S, Yau DKY, Lui JCS (2003) On the effectiveness of movement prediction to reduce energy consumption in wireless sommunication (extended abstract). ACM SIGMETRICS'03, Aan Diego, CA

Feeney LM, Nilsson M (2001) Investigating the energy consumption of wireless network interface in an ad hoc networking environment. INFOCOM 2001 pp. 1548–1557

Garey MR, Johnson DS (1979) Computer and intractability: A guide to the theory of NP-completeness. Freeman, San Francisco

Grossglauser M, Tse DNC (2002) Mobility increase the capacity of ad-hoc wirelss networks. In Proceedings of IEEE INFOOCM'00, Tel Aviv, Israel, pp. 1360–1369

Glodenberg DK, Lin J, Morse AS, Rosen BE, Yang YR (2004) Towards mobility as a network control primitive. In Proceedings of ACM MobiHoc'04, Roppongi, Japan, pp. 163–173

Johnson DB, Maltz DA (1996) Dynamic source routing in ad hoc wireless networks. In: Imielinski and Korth (eds), Mobile Computing. Kluwer Academic Publishers, p. 353

Liu W, Zhang Y, Lou W, Fang Y (2004) DELAR: Device-energy-load aware relaying framework in heterogeneous wirless ad hoc networks. *IEEE Milcom 2004*

Liu W, Lou W, Fang Y (2005) An efficient QoS routing algorithm for delay sensitive applications. Computer Networks 47(1):87–104

Reeves DS, Salama HF (2000) A distributed algorithm for delay-constrained unicast routing. IEEE/ACM Transaction on Networking. 8(2):230–250

Yoon J, Liu M, Noble B (2003) Sound mobility models. In Proc. of ACM MobiCom'03. September 2003, San Diego, CA

Ye Z, Krishnamurthy SV, Tripathi SK (2003) A framework for reliable routing in mobile ad hoc networks. INFOCOM 2003

Zhao W, Ammar M, Aegura E (2004) A Message Ferry Approach for Data Delivery in Sparse Mobile Ad Hoc Networks. ACM MobiCom'04, pp. 187–198