A Location-aided Power-aware Routing Protocol in Mobile Ad Hoc Networks

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***Abstract*– In multi-hop wireless ad-hoc networks, designing energy-efficient routing protocols is critical since nodes are power-constrained. However, it is also an inherently hard problem due to two important factors: First, the nodes may be mobile, demanding the energy-efficient routing protocol to be fully distributed and adaptive to the current states of nodes; Second, the wireless links may be uni-directional due to asymmetric power configurations of adjacent nodes. In this paper, we propose a location-aided power-aware routing protocol that dynamically makes local routing decisions so that a near-optimal power-efficient end-to-end route is formed for forwarding data packets. The protocol is fully distributed such that only location information of neighboring nodes are exploited in each routing node. Through rigorous theoretical analysis for our distributed protocol based on greedy algorithms, we are able to derive critical global properties with respect to end-to-end energy-efficient routes. Finally, preliminary simulation results are presented to verify the performance of our protocol.**

I. Introduction

Wireless ad-hoc networks are dynamically formed by mobile nodes with no pre-existing and fixed infrastructures. In order to provide communication throughout the network, the mobile nodes must cooperate to handle network functions, such as packet routing. The nodes may be mobile with diverse mobility patterns, and may be severely power-constrained for accomplishing their tasks. Such observations pose significant challenges to design *energy-efficient* packet routing protocols while still accommodating node mobility. For such protocols to scale to larger ad-hoc networks, localized algorithms need to be proposed that completely depend on local information. The key design challenge is to derive the required global properties based on these localized algorithms.

In previous work, the general problem of designing power-aware protocols to construct power-efficient routes has been extensively studied [1], [2], [3], [4], [5], particularly in the backdrop of stationary ad-hoc networks such as sensor networks. The general assumption is that each node is able to dynamically adjust its transmission range to reach fewer neighboring nodes, thus saving power whenever possible. Various goals may be achieved by such energy-efficient protocols, such as maximizing lifetime of the nodes [4], or minimizing energy consumption for end-to-end paths [1]-[3].

For example, in the work of Rodoplu et al. [3] and its extensions [1], [2], each node may adjust its transmission power by a local algorithm. The local decisions on all nodes collectively form a subgraph of the maximum-powered network, which guarantees global network connectivity. If a distributed Bellman-Ford algorithm is applied for route discovery in such a subgraph, the power consumption on end-to-end paths may be minimized to be near-optimal. However, there are still unsolved problems that previous works have not addressed. First, the power-efficient protocols are designed for stationary sensor networks, where the construction of a global power-efficient sub-network is feasible. However, when *node mobility* is considered, previous protocols become less efficient, since the subgraph needs to be dynamically maintained whenever nodes move. Second, *uni-directional* wireless links between nodes are natural side-effects of dynamic power adjustments in each individual node, due to asymmetric power configurations in neighboring nodes. In previous work [1]-[3], such properties are not explicitly mentioned or taken into consideration. However, this may significant affect the design of energy-efficient routing protocols.

To address these open problems, we propose *LAPAR*, a new *location-aided power-aware routing* algorithm as an extension to the previous work. In LAPAR, a forwarding node constructs its relay regions based on the position of its neighbors, and forwards a data packet to the specific neighboring node whose relay region covers the destination. If there are more than one neighbors that are able to cover the destination, the algorithm makes *greedy* choices to determine the next hop to forward the packet. In addition, we also propose an alternative backup algorithm where the greedy algorithm fails to discover a power-efficient route. Our algorithm addresses existing open problems in previous work in the following two aspects. First, our algorithm does not attempt to construct a global power-efficient sub-network before making routing decisions. All such decisions are made locally within the nodes, based solely on local information about locations of neighboring nodes. As a result, our algorithm not only scales well to larger ad-hoc networks, but also requires no additional overhead in maintaining the topology of a global power-efficient subgraph when node mobility is present. Second, throughout the design of our algorithm, we have explicitly taken uni-directional wireless links into consideration.

In addition to the work related to power-efficient algorithms, *location-aided routing* protocols such as Location-aided Routing (LAR) [6] or Greedy Perimeter Stateless Routing (GPSR) [7] were also proposed to make informed routing decisions based on information about node locations. LAPAR is different from previous work related to location-aided routing in that previous work do not consider energy efficiency when making routing decisions. While in our work, minimizing the power consumption on end-to-end routes is the primary objective. In particular, the objective of previous algorithms is to discover a shortest-path route that reaches the destination with the smallest number of intermediate hops; while our algorithm aims at minimizing the energy consumption in transmitting a packet. This may lead to more intermediate relaying nodes within the discovered route, since the channel path loss model stipulates that the dependency between nodal transmission power p and distance d is $p \sim 1/d^n$, where $n \geq 2$. With such a model, relaying information with additional nodes may result in lower power consumption than increasing the transmission power to communicate directly.

The remainder of this paper is organized as follows. In Section II we clearly define our system model and assumptions. In Section III, we show the details of *LAPAR*, our location-aided power-aware routing protocol, while presenting rigorous theoretical analysis of its important properties. We show preliminary simulation results in Section IV. Section V concludes the paper.

II. Model

We model the wireless ad-hoc network as a set V of n nodes deployed in a two-dimensional area, where no two nodes are in the same position. We assume each node is aware of its own position through the support of GPS devices. We further assume the existence of location management services so that each node is aware of the positions of other nodes. Finally, we assume that the nodes may be mobile, i.e., positions of nodes may change over time.

We consider the most common channel path loss model, i.e., $p \sim 1/d^n$, where p denotes the transmission power, and d denotes the distance between the antennas of transmitter and receiver. The exponent n is determined from field measurements, which is typically a constant between 2 and 4. Moreover, we assume that a node is able to adjust the transmission power, but not beyond a maximum power P_{max}. We further assume the existence of an underlying MAC layer. Finally, uni-directional wireless links are considered.

Intuitively, given a path loss model of $p \sim 1/d^n$, relaying packets using additional nodes may *in some cases* result in lower power consumption than communicating directly. In order to investigate the implications of location information on power-efficient transmission, we present the following model that accurately shows the circumstances that a relay is needed; and if so, the particular node that serves as the relay. We consider three nodes in a two-dimensional plane, denoted by s, r and d. The *sender*, s, sends data packets to the *destination*, d. If s uses r as its next hop to forward packets to d, node r is referred to as a *relay* for s. The physical distance between node i and j is denoted as d_{ij}, where $i, j \in V$. We use $i \rightarrow j$ to represent that there is an asymmetric link from i to j, i.e. i could transmit packets to j directly. We use $i \xrightarrow{n} j$, $n \geq 1$ if i is able to reach j with n hops, i.e., there are $n-1$ nodes $v_1, v_2, \ldots, v_{n-1}$ so that $i \rightarrow v_1 \rightarrow v_2 \rightarrow \ldots \rightarrow v_{n-1} \rightarrow j$. We use $i \xrightarrow{*} j$ to represent the situation where there exists $n \geq 1$ such that $i \xrightarrow{n} j$.

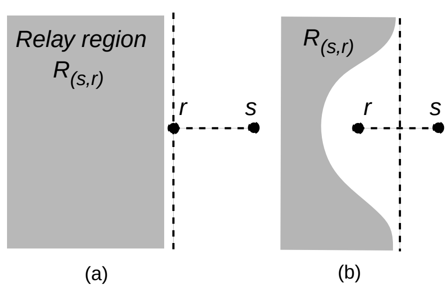

Fig. 1. Relay region with a path loss model of (a) $p \sim 1/d^2$ (b) $p \sim 1/d^4$

Definition 1: The *relay region* $R_{(s,r)}$ of a sender-relay node pair (s, r), where $s \rightarrow r$, is defined as

$$R_{(s,r)} \equiv \{i | {d_{sr}}^n + {d_{ri}}^n \leq {d_{si}}^n, i \neq r\} \quad (1)$$

Figure 1 illustrates the relay region of (s, r) with power exponents $n = 2$ and $n = 4$. Intuitively, the *relay region* is the set of destination nodes where relaying from r is more power-efficient for s. We thus have the following.

Lemma 1 For any $d \in R_{(s,r)}$, if $s \rightarrow d$, then $s \rightarrow r \rightarrow d$, and $P_{s \rightarrow r \rightarrow d} \leq P_{s \rightarrow d}$.

where $P_{s \rightarrow r \rightarrow d}$ denotes the power required to transmit a packet from node s to d via the relay node r, and $P_{s \rightarrow d}$ denotes the power for transmitting from node s to d directly.

Proof: We use T_s to denote the transmission range of node s when it uses its maximum power. If node $s \rightarrow d$ and $d \in R_{(s,r)}$, then $d \in T_s \cap R_{(s,r)}$. From Figure 2, we may observe that $T_s \cap R_{(s,r)} \subset T_r$ always holds, if we assume that the maximum power P_{max} is identical for all nodes. We then have $r \rightarrow d$. Since the path loss model is $p \sim 1/d^n$, assuming $p = k/d^n$, we have $P_{s \rightarrow r \rightarrow d} = k{d_{sr}}^n + k{d_{rd}}^n$ and $P_{s \rightarrow d} = k{d_{sd}}^n$. Since $d \in R_{(s,r)}$, by Definition 1, we have $P_{s \rightarrow r \rightarrow d} \leq P_{s \rightarrow d}$. ■

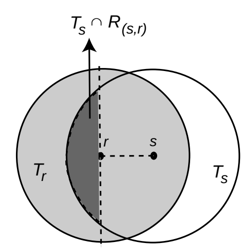

Fig. 2. Relationship among T_s, T_r and $R_{(s,r)}$

Lemma 2 For any $d, r' \in R_{(s,r)}$, if $s \rightarrow r' \xrightarrow{*} d$, then $s \rightarrow r \xrightarrow{*} d$, and $P_{s \rightarrow r \xrightarrow{*} d} \leq P_{s \rightarrow r' \xrightarrow{*} d}$.

Lemma 2 shows that, for a destination node $d \in R_{(s,r)}$, compared with any other node r' in the relay region of (s, r), the relay node r is the most power efficient relay from s to d.

Proof: Since $s \rightarrow r'$, and $r' \in R_{(s,r)}$, by Lemma 1, we have $s \rightarrow r \rightarrow r'$. Therefore, if $s \rightarrow r' \xrightarrow{*} d$, then $s \rightarrow r \rightarrow r' \xrightarrow{*} d$, i.e., $s \rightarrow r \xrightarrow{*} d$. Also, $P_{s \rightarrow r \xrightarrow{*} d} = P_{s \rightarrow r \rightarrow r' \xrightarrow{*} d} = P_{s \rightarrow r} + P_{r \rightarrow r'} + P_{r' \xrightarrow{*} d} \leq P_{s \rightarrow r'} + P_{r' \xrightarrow{*} d}$, which is $P_{s \rightarrow r' \xrightarrow{*} d}$. ■

Lemma 3 (a) For any sender-relay pair (s, r), $s \notin R_{(s,r)}$; (b) If $d \in R_{(s,r)}$, then $r \notin R_{(s,d)}$; (c) If $r_1 \in R_{(s,r)}$, $r_2 \in R_{(s,r_1)}$ $\ldots r_m \in R_{(s,r_{m-1})}$, then $r \notin R_{(s,r_m)}$.

Proof: (a) This is trivially true. (b) Suppose on the contrary, $r \in R(s, d)$, by Definition 1, ${d_{sr}}^n + {d_{rd}}^n \leq {d_{sd}}^n$, $d_{rd} > 0$ and ${d_{sd}}^n + {d_{rd}}^n \leq {d_{sr}}^n$, which is a contradiction. (c) may be similarly proved. ■

The above discussions only consider one sender-relay pair, we now consider all the possible relay candidates for the sender by introducing the following definition:

Definition 2: N_i, the *set of neighbors* of node i, is the set of nodes to which node i is able to send a packet with transmission power P_{max}. Each node in N_i is referred to as a neighbor of node i.

Each node j in N_i can potentially serve as a relay for the sender i. Assuming a path loss model of $p \sim 1/d^2$, Figure 3 shows an example where the relay regions of nodes in N_i are plotted individually.

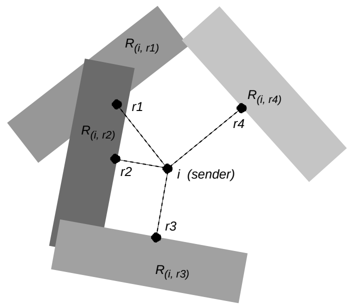

Fig. 3. Relay regions of nodes in N_i

As shown in Figure 3, some nodes in N_i is covered by the relay region of other nodes in N_i. For example, r_1 lies in $R_{(i,r_2)}$. From Lemma 2, it is more power efficient if we use node r_2 as the relay for transmissions from i to r_1. Thus, the relay region of r_1 needs to be merged with the relay region of r_2. The *merge* algorithm for relay regions of each node in N_i is given as follows, assuming that i is the sender and $j \in N_i$:

merge(j)
  for each $k \in N_i$, $k \neq j$
    if $k \in R_{(i,j)}$
    {
      $R_{(i,j)} = R_{(i,j)} \cup \text{merge}(k)$;
      mark(k);
    }
  return $R_{(i,j)}$

Such a recursive algorithm calculates a merged relay region for j, and marks all nodes in N_i that can use j as a relay.

After each neighbor j of node i runs the merge algorithm, a fully merged relay region graph is derived. We denote RC_i as $N_i - \{j|$ j is marked, $j \in N_i\}$, which is the set of relay candidates for node i. Figure 4 illustrates the relay regions and the corresponding relays of node i after merging.

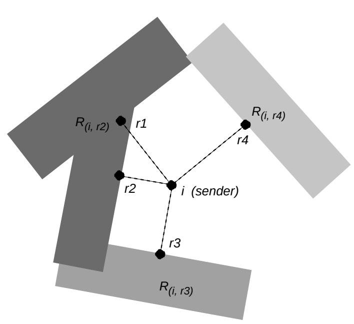

Fig. 4. Relay regions of N_i after the *merge* algorithm

Theorem 1 *Correctness of the* merge *algorithm.* (a) The *merge* algorithm always terminates; (b) All derived properties of a relay region still hold after merging.

Proof: (a) We first prove *merge(j)* always terminates, i.e., there is no loop in recursive calls in *merge(j)*. This can be derived from the property of relay region shown in Lemma 3. No node may appear twice as the parameter in the recursive call. Since there are a finite number of neighbors in N_i, *merge(j)* always terminates for any $j \in N_i$, and the time complexity of *merge(j)* is $O(|N_i|)$. (b) From Lemma 2 and Definition 1, this part may be straightforwardly derived.

Previous discussions have introduced our system model that focuses on the concept of *relay regions*. From the viewpoint of each node, the relay regions of its neighbors have divided the entire two-dimensional plane into multiple sections. In the next section, we will show that the divisions will be used to decide how to forward the message.

III. Algorithm

In this section, we present *LAPAR*, our location-aided power-aware routing protocol. Under LAPAR, packets are marked by their sender node with the locations of their destination nodes. As a result, a forwarding node is able to make an independent decision based only on its local information.

A. The LAPAR Algorithm

We adopt a greedy algorithm to compute global near-optimal power-efficient routes based on the local optimal choice for the next forwarding node. Particularly, if s is the sender and d is the destination, s first computes and merge the *relay regions* of its neighbors (i.e., nodes in N_i) using the *merge* algorithm previously shown. As shown in Figure 4, the relay regions of s divide the entire two dimensional region into multiple *sections*. The routing decision is made depending on which *section* covers the location of d.

There are three possibilities when choosing the section that covers d.

1. Node d lies in the relay region of only one neighbor, e.g., node r. In this case, r is chosen as the next hop to forward packets to d;
2. Node d lies in the intersection of relay regions of multiple neighbors, e.g., $r_1, r_2, \ldots, r_m$. There are m relay candidates for relaying packets from s to d. In this case, we adopt a *greedy* approach to make routing decisions, and choose the neighbor r_k that has a minimum ${d_{sr_k}}^n + {d_{r_k d}}^n$ among all relay candidates;
3. Node d maintains a position covered by none of the relay regions of nodes in N_i. In this case, the greedy routing algorithm fails. There are three reasons for such routing failure. First, it may be a temporary network partition due to node mobility, where there is no directed path from s to d at all. Second, it may be a incorrect greedy decision made in upstream nodes. Finally, it may be caused by inaccurate or out-of-date location information, due to the node mobility. We will present our solution to cope with such failures shortly.

The LAPAR algorithm, executed on each of the forwarding nodes, is formally presented as follows.

We now proceed to present some further analysis and discussions with respect to the properties of our LAPAR algorithm.

```
nexthop(s, d)
  if there exist r_1, r_2, ..., r_m
    such that d ∈ R_(s,r_1) ∩ R_(s,r_2) ∩ ... ∩ R_(s,r_m)
  then nexthop(s, d) = r_k
    where d_{s r_k}^n + d_{r_k d}^n = min(d_{s r_i}^n + d_{r_i d}^n),
        for i ∈ {1...m}
  else
    greedy forwarding fails.
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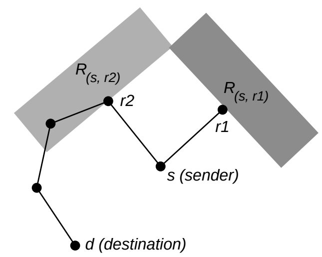

Fig. 5. node i can not determine its next hop by greedy search

B. The Loop Free Property

Theorem 2 The LAPAR algorithm is a *loop-free* routing algorithm.

Proof. Assume that, on the contrary, there exists a loop in the routing path from sender s to destination d, and let $r_1, r_2, ..., r_m$ be the nodes on that loop. From the algorithm we have: $d \in R(r_1, r_2), d \in R(r_2, r_3), ..., d \in R(r_m, r_1)$. From Lemma 1, we have: ${d_{r_1 r_2}}^n + {d_{r_2 d}}^n \le {d_{r_1 d}}^n$; ${d_{r_2 r_3}}^n + {d_{r_3 d}}^n \le {d_{r_2 d}}^n$; ... ${d_{r_m r_1}}^n + {d_{r_1 d}}^n \le {d_{r_m d}}^n$. This leads to ${d_{r_1 r_2}}^n + {d_{r_2 r_3}}^n + ... + {d_{r_m r_1}}^n \le 0$, which is a contradiction. The algorithm is thus loop free. ■

C. Stateless Routing: Accommodating Node Mobility

Compared to other power-aware routing protocols such as [3], one of the major advantages of *LAPAR* is that it exploits location information of neighboring nodes to make all routing decisions. In other words, the only information required at each node in order to make a packet forwarding decision is the locations of its one hop neighbor. Previous work [3] executes the Bellman-Ford algorithm on a minimum-energy network, which requires frequent distribution of the current topology of the entire network. With the presence of *node mobility*, such approaches would suffer from either out-of-date states or a flooding of triggered updates. It also brings large message exchange overhead to the network, which by itself consumes nodal power. In contrast, LAPAR is nearly *stateless* – each node only needs to be aware of its neighbors' positions and requires propagation of topology information for only a single hop. The self-describing nature of location information is the key in achieving such stateless properties.

D. Handling of Routing Failures

However, LAPAR suffers from the same problem as other location based routing algorithms: there are possibilities that greedy forwarding may fail [6], [7]. Figure 5 illustrates an scenario where greedy search based solely on location information of the destination is impossible.

We adopt a similar approach as proposed in GPSR [7] to discover a path to destination when greedy forwarding fails. In GPSR, a packet would be forwarded in two modes: "greedy", and "perimeter". Special rules are designed to forward packets in the "perimeter" mode when the greedy algorithm fails. It was shown that this approach is loop free and efficient in finding a feasible path.

In *LAPAR*, a packet is also forwarded in two modes: "greedy", and "non-greedy". Initially, a packet is marked as "greedy". A sender or relay node always attempts to forward a "greedy" packet to its downstream neighbor using the greedy algorithm previously presented, which is most power efficient. Such behavior continues until the greedy forwarding algorithm fails. Such failures may be due to incorrect greedy decisions in upstream nodes, or inaccurate location information of the destination. In order to mitigate the effects of inaccurate location information, the relay node first updates the location of destination when it can not locate the next hop using the greedy algorithm, then proceeds to examine whether greedy forwarding is possible after the location update. If it is still impossible, the relay node will switch the packet into the "non-greedy" mode. Similar to the "perimeter" mode in GPSR, the packet in this mode will be forwarded according to the right-hand rule on a *planar graph* until either the destination is reached or a greedy algorithm would be applied again.

E. Construction of a Power-efficient Planar Graph

We show an algorithm to construct such a power efficient planar graph. Denote $G' = (V', E')$ as such a planar graph. The *construction algorithm* is shown as follows.

```
V' = V; // V is the set of all nodes deployed
E' = φ;
  for each node i in the plane
    for each j ∈ RC_i
      E' = E' ∪ (i, j);
```

We continue to show that if the path loss model is $p \sim 1/d^2$, i.e., the power exponent $n = 2$, we have constructed a planar graph.

Theorem 3 *Correctness of the construction algorithm. G'* derived by the construction algorithm is a planar graph, if the power exponent $n = 2$ in the path loss model.

Proof: We prove by showing G' is a *Gabriel Graph (GG)*, a well-known planar graph defined as follows:

An edge (u, v) exists between nodes u and v, if

$$\forall w \neq u, v : {d_{uv}}^2 < {d_{uw}}^2 + {d_{vw}}^2 \quad (2)$$

Assume there exists an edge $(u, v) \in E'$ so that there is a w that satisfies ${d_{uv}}^2 \ge {d_{uw}}^2 + {d_{vw}}^2$. Node w is a neighbor of u, since $d_{uw} < d_{uv}$ from above equation and v is a neighbor of u. Now consider the relay region of (u, w). By Definition 1, we observe that $v \in R_{(u,w)}$. From the *merge* algorithm, we observe that v will be screened during the relay candidate computation. We thus have $v \notin RC_u$. By the construction algorithm, (u, v) will not appear in E', which is a contradiction. ■

As we have shown, the construction of such a planar graph is fully integrated within the computation of relay candidates and their relay regions. Thus, no further overhead will be introduced. More importantly, the derived planar graph is still power-aware.

Finally, We wish to point out that the power consumption function used in Definition 1 may be replaced with a *generic cost function*, which integrates the *price* of consuming nodal energy reserves. For example, d_{xy} could be replaced by $f(E_x, E_y, P_{x \to y})$, where E_x, E_y are prices for consuming energy on node x and y. E_x will increase if the power reserves of node x decreases. Via this approach, our algorithm may also serve the purpose of maximizing the life time of networks.

IV. Simulation

We show our preliminary simulation results in this section. We first simulate the LAPAR algorithm in a stationary multi-hop wireless network where nodes are fixed. The nodes are uniformly distributed over a square region of 400 meters on each side. A sender node may reach a node 100 meters away at its maximum transmission power P_{max}. We first investigate how the number of nodes could affect the *success ratio* of our greedy routing algorithm. We define the *success ratio* as $\frac{\text{number of successfully discovered route}}{\text{number of connected route}}$. Figure 6 illustrates such a relationship. As the number of nodes deployed in this region increases, the density and connectivity increase. The success rate increases accordingly. Figure 6 also shows that the greedy algorithm enjoys a high success ratio.

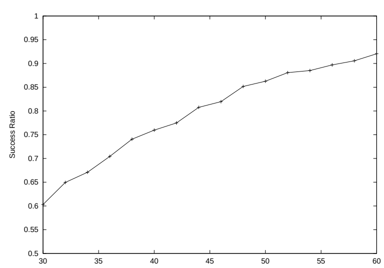

Fig. 6. Success ratio of LAPAR algorithm in the *Greedy* mode

We then proceed to compare the power consumption of LAPAR with an example location-aided routing protocol, GPSR [7]. Figure 7 illustrates the percentage of power saved versus the number of nodes, where the percentage of power saved is calculated as $\frac{\text{power usage of GPSR - power usage of LAPAR}}{\text{power usage of LAPAR}}$.

Finally, we measure LAPAR's energy consumption levels with node mobility present. Node mobility follows the following model: 50 nodes are initially uniformly deployed over a square region of 400 meters on each side. The velocity of each node in each coordinate direction is uniformly distributed on the interval $(-V_{max}, V_{max})$. V_{max} is varied to observe how the power consumption changes accordingly. Figure 8 shows such a relationship. It shows that the average power consumption per unit distance is significantly lower and the motion of nodes does not

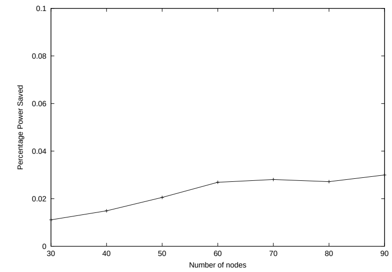

Fig. 7. Comparison between GPSR and LAPAR: Average Power Consumption

significantly affect the power consumption. This result verifies our previous argument that LAPAR performs well with node mobility.

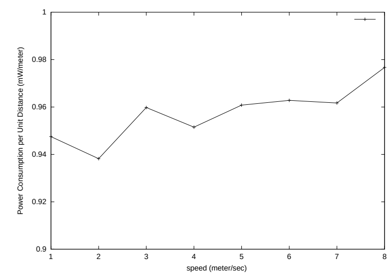

Fig. 8. Average Power Consumption with Node Mobility

V. Conclusions and Future Work

In this paper, we proposed a location-aided power-aware routing protocol (LAPAR) in mobile ad-hoc networks. Our protocol is fully distributed, while only location information of neighboring hosts is exploited to make a routing decision. We have shown both theoretically and experimentally that our protocol is power-efficient and solves several open problems that were not addressed in previous work. As part of the future work, we will explore the effects of inaccurate location information on the LAPAR algorithm.

References

[1] P. Bahl R. Wattenhofer, L. Li and Y. Wang, "Distributed Topology Control for Power Efficient Operation in Multihop Wireless Ad Hoc Networks," in *Proceedings of INFOCOM '01*, 2001.

[2] L. Li and J. Halpern, "Minimum-Energy Mobile Wireless Networks Revisited," in *Proceedings of IEEE Conference of Communications (ICC '01)*, 2001.

[3] V. Rodoplu and T. Meng, "Minimum Energy Mobile Wireless Networks," *IEEE Journal of Selected Areas in Communications*, vol. 17, no. 8, pp. 1333–1344, 1999.

[4] J. Chang and L. Tassiulas, "Energy Conserving Routing in Wireless Ad-hoc Networks," in *Proceedings of INFOCOM '00*, 2000, vol. 1, pp. 22–31.

[5] M. Woo S. Singh and C. Raghavendra, "Power-aware Routing in Mobile Ad-hoc Networks," in *Proceedings of the Fourth ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom '98)*, 1998, pp. 181–190.

[6] Y. Ko and N. Vaidya, "Location-Aided Routing(LAR) in Mobile Ad Hoc Networks," in *Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom '98)*, 1998, pp. 66–75.

[7] B. Karp and H. Kung, "GPSR:Greedy Perimeter Stateless Routing for Wireless Networks," in *Proceedings of the Sixth Annual International Conference on Mobile Computing and Networking (Mobicom '00)*, 2000, pp. 243–254.