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An Improved Router Placement Algorithm based on Energy Efficient Strategy for Wireless Networks

Yan Shi
Educational Technology and
Network Information Center
Mudanjiang Medical University
Mudanjiang, China, 157011
mdjmu2009@sina.com

Fu Jia
Library
Mudanjiang Medical University
Mudanjiang, China, 157011
fujia1981@sina.com

Yu Hai-tao
Network Information Center
Mudanjiang University
Mudanjiang, China, 157011
yu_ht2009@sina.com

***Abstract*—In many applications of wireless systems, a minimum energy broadcast routing from a given source unit has to be computed repeatedly and quickly. We present router placement (RP) for energy-constrained wireless networks, and prove RP algorithms can minimize total energy consumption. We derive the RP problem for multi-hop wireless networks, and develop an efficient heuristic solution for them. Multi-router placement is regarded as a clustering optimization problem. The routers and nodes are regarded as cluster heads and cluster members. We also design a heuristic that discovers the central area of a multi-hop network, and resolves the RP problem with multi-hop connectivity. Our results imply that our RP methods reduce the energy consumption of wireless networks by up to 55% compared with grid networks.**

Keywords-Router Placement Algorithm; Energy Efficient Strategy; Wireless Networks

I. INTRODUCTION

A mobile ad hoc network (MANET) is a wireless, multi-hop, mobile network in which network nodes may operate as intermediate routers or relay stations. Since it requires no preinstalled infrastructure, it is suitable for such applications as an emergency communications network, a vehicular network, or a sensor network. These networks contain a massive number of small wireless transceivers powered by batteries. It is very hard to replace their energy sources, so the energy efficiency of such networks is a key aspect of successful network operation. Recently, various methods have been proposed that use random, predictable, or controlled node mobility for conserving communication energy and improving network performance [1], [3], [10]. They usually assume a flat network structure in which movable nodes act as relays from the source to the destination nodes, so they first need to identify which nodes are traffic sources, and which are destinations. However, often the traffic pattern is not known a priori, and source and destination nodes are randomly determined. In such cases, the previous schemes cannot place relay nodes at the most appropriate locations.

This study approaches MANET energy conservation from a different perspective. We assume a two-layered hierarchical network structure consisting of user nodes and mobile routers, where a router can be moved to any location. We further assume that routers have a separate wireless channel for communication between them, and they have sufficiently large energy sources. Consider the following example. Suppose N fire fighters with wireless transceivers are on a mission to extinguish a forest fire. We dispatch R unmanned aerial vehicles (UAVs) to assist with network communication. Where should we place the UAVs to minimize energy consumption of the fire fighters' communication devices? In addition to reducing the energy consumption of user devices, mobile routers are often needed to maintain connectivity when radio obstructions such as buildings or trees exist between user nodes. Figure.1 illustrates a MANET in which inter-node communication is costly compared to that between nodes and routers due to signal obstruction by trees. In such cases, mobile routers hovering above can relay data between user nodes, when direct communication between users is not possible.

We model this problem as a clustering problem composed of unconstrained convex optimization sub problems. We treat routers as cluster heads, and aim to minimize the energy consumption of uplink communication, i.e., communication from user nodes to routers. As the clustering problem is NP hard, we develop an efficient heuristic method based on the K-means algorithm [4], which is widely used for clustering. Simulation results show that our router placement algorithm produces near-optimal solutions with high probability.

II. OPTIMIZAIN ROUTER DEPLOYMENT

This section describes our assumptions concerning the wireless channel and network traffic. Then the proposed router placement algorithm is presented.

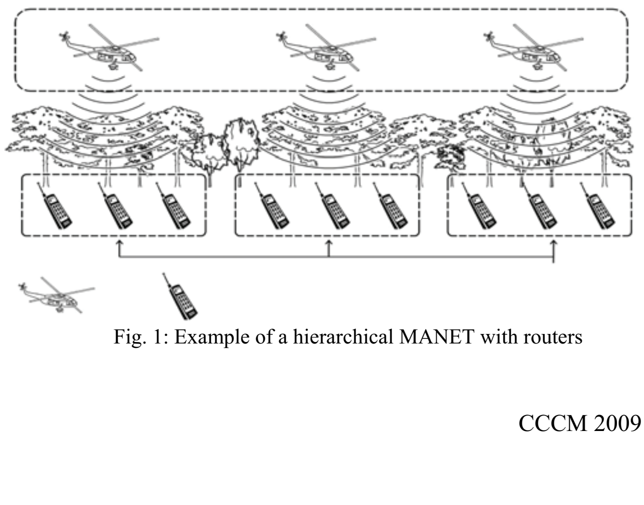

Fig. 1: Example of a hierarchical MANET with routers

A. Communication Model

As in [1], [3], [6], we assume that the communication power from transmitter T to receiver R is given by

$$Pow(T,R) = k_0 + k_1 \cdot Dist(T,R)^{\alpha} \quad (1)$$

where Dist(T,R) denotes the distance between T and R, and the path loss exponent α is usually assumed to range between 2 and 6. The parameters k0, k1, and α vary according to the radio environment and the transceiver's bandwidth.

We assume that routers can determine the locations of all nodes using appropriate localization algorithms. We also allow source and destination nodes to be randomly chosen. Data can be generated at any node, and can be delivered to any other node, and the source-destination pair can frequently change over time.

We assume a network architecture resembling the near-term digital radio (NTDR) network [5], [9]. In Fig. 1, in order for a source node x to send data to a destination y, node x either directly transmits the data to the nearest router R(x), or sends it over the shortest multi-hop path to R(x). Then R(x) sends the data to the router R(y) of the destination y through a separate communication channel. Eventually, R(y) sends the data to the final destination y. Hence, the inter-router network provides the network backbone, and the cluster head serves as the gateway.

B. Single-Router Placement Optimization (1-RP)

We first consider the case that only one router exists, i.e, R = 1. Suppose that N nodes are placed at locations denoted by vectors pi ($1 \le i \le N$). Throughout this paper, the location vector of node pi is written as pi consistently. The nodes communicate with the router, and we want to minimize the uplink communication energy consumed by the nodes by controlling the router location x. The RP problem is then: What is the optimal location x?

Algorithm 1: 1-RP algorithm

Input: {pi} and x^0; node locations, and an initial guess of the router location

Output: x; router location

1. Set the router location x to a centroid location m; x ← m.
2. Find the set B_i of neighbors of p_i.
3. Compute the total transmission time $T(p_j)$ for each $p_j \in B_i$.
4. Compute the router location x^* by solving

$$Minimize \sum_{P_j \in B_i} T(p_j)(k_0 + k_1 \| x^* - P_j \|^{\alpha}) \quad (2)$$

Set x to one of x^* and x^0, which incurs less energy cost.

5. Find the shortest paths from all nodes to the router.
6. Find the set B_x of neighbors of the router.
7. Compute $T(p_j)$ for each $p_j \in B_x$.
8. Compute the router location x by solving

$$Minimize \sum_{P_j \in B_x} T(p_j)(k_0 + k_1 \| x - P_j \|^{\alpha}) \quad (3)$$

Let $\tau(p_i)$ be the number of data bits sent from node p_i. Note that this number is measured at the application layer, so the number of bits for forwarding other nodes' data is not accounted for. We define a centroid node m of a graph G =(P,E) as a node that satisfies $m = \mathrm{argmin}_{u \in P} \sum_{v \in P} \{\tau(v) \cdot d(u, v)\}$ where d(u, v) denotes the multi-hop distance between nodes u and v, i.e., the sum of edge weights along the shortest path between u and v. Intuitively, a centroid is a node that can receive data from all other nodes at the minimum energy cost. Note that a graph can have multiple centroids. In our application, the weight w(u, v) of an edge (u, v) is defined as the communication cost between two nodes given by (1);$w(u,v)= k_0+k_1\|u-v\|^{\alpha}$. We also define a centroid location m as the location of the centroid.

Our proposed 1-RP algorithm is summarized in Algorithm 1.

Step 1 first finds a centroid node pi and the shortest paths tree $G_i = (P,E_i)$ rooted at pi. Then it sets the router location x to the centroid location m.

Step 2 builds the neighbor set Bi that contains pi and the nodes adjacent to p_i; $B_i = \{p_i\} \cup \{p_j \mid (p_i, p_j) \in E_i\}$.

Step 3 computes the total number of bits T (p_j) for each $p_j \in B_i$. For a node p_j adjacent to the centroid p_i, $T(p_j)$ is defined as the sum of the τ(pm)'s of nodes $\{p_m\}$ in the subtree rooted at p_j . For the centroid p_i itself, T (pi) is defined as τ(pi).

$$T(P_j) = \begin{cases} \sum_{p_m \in Subtree(P_j)} \tau(p_m) & if \ j \neq i \\ \tau(p_j) & if \ j = i \end{cases}$$

The total number of bits $T(p_j)$ is the number of data bits that node p_j transmits including its own data and forwarded data from other nodes in the sub-tree. In order to minimize the total energy consumption, the energy cost function needs to be weighted by T (p_j), not by $\tau(p_j)$.

Step 4 computes the router location x* by solving (2), a convex optimization problem. It is possible that the total energy cost with the new router location x* is greater than that with the initial router location x^0. In that case, we discard the new location x*, and set x to the initial location x^0; otherwise, we adopt the new one, and set x to x*. This is necessary to guarantee convergence of K-RP in Section II-C, which repeatedly executes 1-RP.

Step 5 discovers the shortest paths from the router to all nodes, and builds the shortest path graph $G_x = (P \cup \{x\},E_x)$, where the router x is the root.

Step 6 finds the set B_x of neighbors of the router x; $B_x = \{p_j \mid (x, p_j) \in E_x\}$.

Step 7 computes the total number of data bits T (p_j) for each $p_j \in B_x$ in a manner similar to that in Step 3; T (p_j) = $\sum_{pm \in Subtree(pj)} \tau(pm)$.

Finally, Step 8 computes the router location x by solving (3)

C. Multiple-Router Placement Optimization (K-RP)

Now we extend the foregoing technique to solve the multiple router placement problems; see Algorithm 2. It first searches shortest paths from all nodes to all routers, and groups' nodes into clusters. The router placement x_k can then be computed by applying Algorithm 1 to the clusters. These steps are repeated until no change in clustering occurs.

Algorithm 2: K-RP algorithm

Input: $\{p_i\}$, K, and $\{x_k\}$; node locations, the number of routers, and an initial guess of router placement

Output: $\{x\}$; router location

1. Find shortest paths from all nodes to all routers; then group nodes into clusters such that

$$p_i \in C_k \text{ where } k = \text{argmin}_j\, d(p_i, x_j)$$

2. For each cluster C_k, compute the router location x_k by applying Algorithm 1. Repeat Steps 1 and 2 until no change in clustering occurs.

Convergence of K-RP can be proved as follows. For given router placement, Step 1 computes clustering only in the direction of total energy decrease. For given clustering, router placement determined by Step 2 only decrease the total energy. On the other hand, the total energy is obviously lower bounded. Thus the K-RP algorithm always converges.

III. PERFORMANTCE EVALUATION

This section presents simulation results with the router placement algorithm K-RP described in Section II. First we describe the simulation environment and assumptions about the radio channel model. Nodes and routers are placed on a 1 × 1 km^2 plane. We assume the following radio parameters, partly taken from [2]: radio attenuation exponent $\alpha = 4.0$; transmission power Pow = 281.8 mW for transmission distance Dist = 250 m. Accordingly, we set the transmission power coefficients k_0 and k_1 in (1) to $k_0 = 0$ W and $k1 = 7.2141 \cdot 10^{-11}$ W/m^4, respectively. To our knowledge, the NTDR network structure has not been adopted for node placement optimization, so no experimental data for comparison purposes is available. For this reason, in order to evaluate efficiency of the K-RP algorithm, we compare the power consumption by two different network structures: a network in which the router placement are determined by the K-RP algorithm; and a grid network structure which resembles the routing backbone of sensor networks [8] and cellular networks [7]. The number N of nodes is set to 320, and the number K of routers varies from 9 to 64. In the grid structure, the 1×1 km^2 plane is divided into K squares, and a router is located at the center of each square. For a given K, 1000 different sets of random node locations were considered to compute the average power consumption; for each node arrangement, the K-RP algorithm was repeated 20 times to get the best router placement. Figure 2(a) shows the simulation results for power consumption by the K-RP and the grid structure. It can be seen that both the grid and the K-RP structures consume less power as the number of routers increases. On the other hand, Fig. 2(b) shows the ratio between power consumption by the K-RP and the grid structure. From these results, we conclude that K-RP effectively reduces the total power consumption, and the relative saving increases as the number of routers grows.

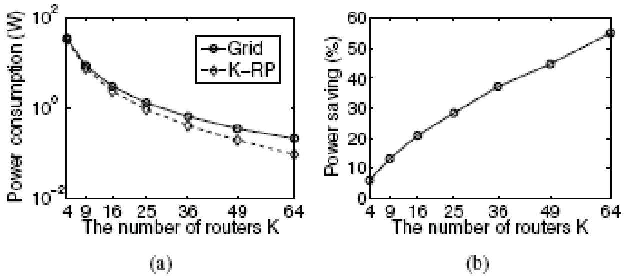

Fig. 2: Power consumption by a grid network structure and a *K*-RP structure; (a) total power consumption by the grid and *K*-RP; and (b) the power saving obtained by *K*-RP.

IV. CONCLUSION

We have investigated several key router placement problems for energy-efficient wireless networks. We modeled multiple router placements as a clustering optimization problem, and developed efficient heuristics for single-hop and multi-hop communication. The simulation results confirm that the proposed algorithms are effective in substantially reducing energy consumption of wireless networks. Though our experiments focused on two-dimensional cases, the algorithms can be readily adapted to 3-dimensional applications. Furthermore, the techniques proposed for router placement could be extended to solve a wider variety of optimization problems such as: how to maximize the lifetime of the network when nodes have different battery capacities; how to determine optimal router placement without violating the topographic constraints defined by buildings, trees, etc.; and how to maximize the total throughput from nodes to routers.

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