Maximizing Battery Life Routing in Wireless Ad Hoc Networks

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***Abstract*—Most wireless ad hoc networks consist of mobile devices which operate on batteries. Power consumption in this type of network therefore is paramount important. To maximize the lifetime of an ad hoc network, it is essential to prolong each individual node (mobile) life through minimizing the total transmission energy consumption for each communication request. Therefore, an efficient routing protocol must satisfy that the energy consumption rate at each node is evenly distributed and at the same time the total transmission energy for each request is minimized. To devise a routing protocol meeting the above two conflict objectives simultaneously is very difficult due to the NP hardness of the problem. Instead, an approximation solution is desirable and appreciated.**

In this paper we focus on developing power-aware routing algorithms which find routing paths that maximize the lifetime of individual nodes and minimize the total transmission energy consumption, thereby prolong the life of the entire network. In particular, for an ad hoc network consisting of the same type of battery mobile nodes, two approximation algorithms are proposed. The running times of the proposed algorithms are determined by the accuracies of the approximation solutions. Compared with a previously known result, our algorithms have less energy overhead and can be implemented in a distributed environment. For an ad hoc network equipped with different types of battery mobile nodes, a new power-aware routing protocol is proposed, and the algorithm can also be implemented distributively.

Keywords: *Wireless network, approximate algorithm, power awareness, ad hoc networks, energy conversation optimization.*

I. INTRODUCTION

Ad hoc wireless networks are multi-hop wireless networks consisting of mobile nodes that do not rely on the presence of any fixed network infrastructure, where all nodes cooperatively maintain network connectivity. This type of network is useful in any situation where temporary network connectivity is needed, such as in disaster relief, law enforcement, battlefield, etc. Ad hoc wireless networks usually consist of mobile battery operated computing devices that communicate over the wireless medium. These devices are battery operated and therefore need to be energy conserving so that the battery life of each individual node can be prolonged. Although research continues to reduce the power energy consumption of CPUs, user interface and storage devices, the transmission energy for a packet in wireless channels is still quite significant and may turn out to be the highest energy consuming component of the devices. Hence there is a need for designing minimum energy consumption routing protocols that ensure a longer battery life. For such a protocol design, the existing minimum-hop routing scheme cannot be applied, and a new, power-aware routing scheme that takes the transmission energy into consideration explicitly is urgently needed. The performance of an ad hoc wireless network is dependent on which routing algorithm (protocol) it employed. Unlike cellular networks, the lifetime of mobile nodes will deeply impact on the performance of ad hoc networks. In a cellular network, a reduction in the number of active mobile nodes will reduce the amount of signal interference and channel contentions. However, since the mobile nodes in an ad hoc network need to relay their packets through the other mobile nodes toward the intended destinations, a decrease in the number of participating mobile nodes may lead to the network disconnected, thereby hurting the performance of the network. To prolong the lifetime of each mobile node in the network as well the entire network itself, an ad hoc routing should take into account both the energy consumption at each mobile node and the total energy consumption for each connection request carefully.

A. *Related work*

Ad hoc routing protocols can be roughly classified as table driven routing and source initiated on-demand routing. Table driven approach uses a routing table which is maintained via periodic updates from all the other nodes in the network irrespective of the fact that the network may not be active in terms of data traffic. The on-demand approach, on the other hand, sends out requests for routes to the destination only if the source node has data packets which are to be sent to the destination. Generally speaking, the table driven approach is more expensive in terms of energy consumption as compared to the on-demand approach because of large routing overhead incurred in the former. In this paper we thus focus on on-demand routing. There are a number of studies which aim at developing power-aware routing schemes by incorporating several important metrics into consideration. The most popular one is the *shortest hop* routing including Dynamic Source Routing (DSR) [4], Destination Sequenced Distance Vector (DSDV) [19], Temporally Ordered Routing Algorithm (TORA) [23], Wireless Routing Protocol (WRP) [22] and in the DARPA packet radio protocol [21]. Unfortunately, some of the current metrics have a negative impact on the nodes and network life by inadvertently overusing the energy resources of a small set of nodes in favor of others. To explore the issue of increasing node and network life by using power-aware metrics for routing, several power-aware routing protocols have been suggested recently. For example, Singh et al. [2] introduced power aware cost metrics for routing and designed routing schemes that minimize these metrics. Ramanathan and Rosales-Hain [16] proposed an energy saving scheme by adjusting transmitting power to control the topology of an ad hoc network. Chang and Tassiulas [6] proposed maximizing the network lifetime through avoiding using low power nodes and choosing a shortest path in terms of the energy consumption if the packet rate is known in advance. Gupta and Kumar [14] discussed the critical power at which a node needs to transmit in order to ensure the network is connected. Li et. al [3] considered a residual power routing, which aims to maximize the remaining energy capacity at each node, while keeping the total energy consumption for the routing is bounded. Toh [1] proposed a *conditional max-min battery capacity routing schema*. The basic idea behind this schema is when all nodes in some possible routes between a source and a destination have sufficient remaining battery capacity (i.e., above a threshold), a route with the minimum total transmission energy is then chosen. Since less total energy is required to forward packets for each connection, the relaying load [5] for most nodes will be reduced, and the lifetime of the involved nodes will be extended.

Inspired by the work due to Li et. al [3] and Toh [1], in this paper we first re-examine the problem in a wireless ad hoc network consisting of the same type battery mobile nodes by proposing two approximation algorithms. The proposed approximation algorithms tradeoff the running times and accuracy of the approximation solution obtained. In addition, the proposed algorithms can be implemented in a distributed environment. In an ad hoc wireless network consisting of different types of battery mobile nodes, we provide a new routing protocol called *weighted capacity power-aware routing protocol*, which takes into account the different battery capacities. Unlike Toh's algorithm which does not pay any attention on the remaining capacity of a node until the residual energy capacity of the node is below a given threshold, the proposed algorithm takes the capacity difference among the nodes consideration seriously from the very beginning, and trade-offs the power consumptions at nodes and per route carefully.

The remainder of this paper is organized as follows. Section 2 gives notions and notations. Section 3 presents efficient power-aware routing algorithms and their distributed implementation for an ad hoc wireless network consisting of homogeneous mobiles. Section 4 proposes a new weighted capacity power-aware protocol for an ad hoc wireless network consisting of heterogeneous mobiles. The conclusion is given in Section 5.

II. PRELIMINARIES

An ad hoc wireless network can be modeled by a weighted graph $G = (V, E)$, where V is the set of mobiles (nodes) and E is the set of full-duplex communication links, where $|V| = n$ and $|E| = m$. The weight associated with a link $(u, v) \in E$ is the power level of its two endpoints u and v, and u and v are within the transmission range of each other when they keep their power at this level. Each node has a unique identifier and is equipped with one transmitter and one receiver.

Suppose that a source node u transmits a packet to a destination node v that has a distance $e_{u,v}$ far away from u. Then, the minimum transmission energy $P_{u,v}$ at u is

$$P_{u,v} = ke^{\alpha}_{u,v}, \tag{1}$$

where k and α are constants, and α is typically between 2 and 4. Equation (1) represents an approximation model of power consumption at u, where $\alpha = 2$ if v is not far away from u, $\alpha = 4$ otherwise.

A *residual network* $G_r = (V, E_r)$ of an ad hoc network $G(V, E)$ is defined as follows. Let $p_t(v)$ be the remaining energy capacity of the battery at node v at time t. Unless otherwise specified, in the following we omit the index t and use $p(v)$ instead of

$p_t(v)$ if no confusion is arisen. The battery capacity at v is $C(v)$ initially, and its remaining energy capacity at time t is $p(v)$. If a mobile v_j is within the transmission range of v_i when v_i uses power $p(v_i)$ to transmit packets, then there is a directed edge in G_r from v_i to v_j, and the weight assigned to the edge is ke_{ij}^{α}, following Eq. (1), where $e_{i,j}$ is the distance between v_i and v_j. Clearly, $E_r \subseteq E$.

Let $p(u)$ be the *remaining energy capacity* of a node u at time t. Assume that u and v are the neighboring nodes in a routing path. Then, the *ratio of remaining energy capacity* at u between after and before realizing the routing is defined as

$$\theta(u) = \frac{p(u) - ke_{u,v}^{\alpha}}{C(u)}. \quad (2)$$

Here $\theta(u)$ indicates how much proportional energy in u is left after realizing the routing. The *load ratio* $\theta(G)$ of the network G is then defined as

$$\theta(G) = \min_{u \in V}\{\theta(u)\}. \quad (3)$$

The *power-aware routing problem for a communication request* is formalized as follows. Let P be a routing path consisting of directed links $\langle v_0, v_1\rangle$, $\langle v_1, v_2\rangle$, $\ldots$, $\langle v_{l-1}, v_l\rangle$ in the current residual network G_r for a communication request (s,t) with $s = v_0$ and $t = v_l$. The problem is to find such a path P that (i) minimizing the total transmission energy $W(P) = \sum_{i=0}^{l-1} ke_{v_i,v_{i+1}}^{\alpha}$ in P and (ii) maximizing the minimum ratio of the remaining energy capacity at node v_i in P if $\theta(v_i) = \min_{v_j \in V(P)}\{\theta(v_j)\}$.

In order to minimize the energy consumption for a connection request, a routing path with more hops than another path is favored, which can be explained as follows. Let P be the path consists of links $\langle v_0, v_1\rangle$, $\langle v_1, v_2\rangle$, $\ldots$, $\langle v_{l-1}, v_l\rangle$. Assume that $e_{0,l} = e_{0,1} + e_{1,2} + \ldots + e_{l-1,l}$, then, the cost of P is $W(P) = \sum_{i=0}^{l-1} ke_{i,i+1}^{\alpha} > k(e_{v_0,v_1} + e_{v_1,v_2} + \ldots + e_{v_i,v_{i+1}} + \ldots + e_{v_{l-1},v_l})^{\alpha} = ke_{v_0,v_l}^{\alpha}$ due to that $\alpha \geq 2$. However, it is also well known that an ad hoc wireless network is unreliable and its links can break down at anytime. This means that a longer routing path may take more risks. For a given request from s to t, the problem now is to find a directed path in the residual network G_r from s to t such that the two objectives are met simultaneously. This is a very challenging problem due to that the two conflict objectives are to be optimized. On one hand, if only $W(P)$ is minimized, then, the remaining energy capacities at some nodes in the shortest path P will be drained out very soon, the network will be disconnected, no matter how large the remaining energy capacities of the other nodes left. This is because the network connectivity is fully determined by the setting of the power levels of the nodes in the network, while the power level setting at a node is determined by its remaining energy capacity. On the other hand, if only maximizing the ratio of the remaining energy capacity at each node, it may end up with finding a longer routing path which has the larger $W(P)$. Thus, the best policy is how to trade-off the above two optimization objectives smartly.

III. Routing Algorithms for Homogeneous Mobiles

In this section we deal with an ad hoc network called *a homogeneous mobile network* in which the mobile nodes are equipped with the same type of batteries. For a given communication request, our objective is to devise an efficient routing algorithm for finding a routing path in it with minimizing the total transmission energy consumption and maximizing the minimum residual energy capacity of any node in the path. In the following we show that this problem is NP-hard.

Note that every edge $\langle v_i, v_{i+1}\rangle$ in the residual energy network G_r is associated with a pair of weights, $(ke_{v_i,v_{i+1}}^{\alpha}, \frac{p(v_i) - ke_{v_i,v_{i+1}}^{\alpha}}{C(v_i)})$, where $ke_{v_i,v_{i+1}}^{\alpha}$ is called the first component of the edge and the latter one is called the second component of the edge. It has been shown that finding a restricted path P in a directed weighted graph with minimizing the weighted sum of links in terms of the first component and maximizing the minimum weight of links in terms of the second component in P is NP-hard [20]. Therefore, the power-aware routing problem is NP-hard too. Due to that the problem is NP hard, we focus on providing approximation solutions for it. Specifically, we provide feasible solutions for the problem that maximize the load ratio of the network but bound the total transmission energy consumption in the routing path. Assume that L is the length of a shortest path in the residual energy network G_r from s to t without considering the load ratio of the network. Then, L is a lower bound of the total transmission energy consumption in any routing path for the problem. Our objective, therefore, is to find such a routing path that maximizes the load ratio of the network and bounds its total transmission energy within βL, where $\beta \geq 1$ is constant. It is obvious that this is a relaxation of the original problem. In the following a dynamic programming solution for this relaxation is proposed.

Let $g_v(\theta)$ be an upper bound of the total transmission energy of a routing path from source s to a destination v such that the load ratio of remaining energy capacity at each node in the path is no less than θ, $0 < \theta < 1$. Then, we have

$$g_s(\theta) = 0, \theta = 0, \ldots, \theta_{\max}, \tag{4}$$

$$g_{v_j}(0) = \infty, v_j \neq s, \tag{5}$$

$$g_{v_j}(\theta) = \min\{g_{v_i}(\theta) + ke_{ij}^{\alpha} \mid \frac{p(v_i) - ke_{ij}^{\alpha}}{C(v_i)} \geq \theta, \; v_j\ is\ within\ the\ transmission\ range\ of\ v_i\ if\ v_i\ use\ p(v_i)\ to\ transmit\ packets\}, \tag{6}$$

$$g_t(\theta) \leq \beta L, \tag{7}$$

Given θ and β, a procedure TEST(G_r, θ, β) will be used to check whether G_r contains a routing path for a request from s to t such that the total transmission energy consumption in the path is no more than βL and the load ratio of the network is no less than θ at the same time. That is, TEST finds such a solution that Eqs. (4), (5), (6), and Inequality (7) are satisfied simultaneously, for a given $0 < \theta < 1$. Procedure TEST is presented as follows.

```
TEST(G_r, θ, β)
find a shortest path in G_r from s to t, let L be
the length of the path.
/* L is a lower bound of the total */
/* transmission energy for the request.*/
if   no such path exists
     then   no routing path for the request exists.
          exit;
     else   /* find a routing path for it */
          g_s ← 0;
          parent(s) ← s;
          for  all v ∈ V − {s}   do
               g_v ← ∞;
          endfor;
          for  i ← 1 to n − 1   do
               for  each ⟨u, v⟩ ∈ E_r   do
                    if  ((p(u) − ke^α_{u,v})/C(u) ≥ θ)&
                         (g_v ≥ g_u + ke^α_{u,v})
                         then   g_v ← g_u + ke^α_{u,v};
                                parent(v) ← u;
                    endif;
               endfor;
          endfor;
          if   g_t > βL
               then  return   false;
               else  return   true;
          endif;
endif.
```

A. An approximation algorithm

We now present an approximation algorithm for the problem, which finds a path P from s to t in the network with maximizing the load ratio of the network and bounding the total transmission power consumption in P within βL, as follows.

```
Find_Routing_path(G_r, ε)
     LB ← ε; /* the lower bound of θ */
     UB ← 1; /* the upper bound of θ */
     while   (UB − LB) > ε do
          θ ← (LB+UB)/2;
          if      TEST(G_r, θ, β)
                  then    LB ← θ;
                  else    UB ← θ;
          endif
     endwhile.
```

Theorem 1: There is an approximation algorithm for the problem, which delivers a feasible solution no less than $\theta^* - \epsilon$. The algorithm takes $O((m + n\log n)\log(\frac{1}{\theta_{\max} - \theta_{\min}}))$ time, where $0 < \epsilon < 1$ is a small constant, $\theta_{\min} = \epsilon$, $\theta_{\max} = 1$, and θ^* $(= \max_{v \in V}\{\theta(v)\})$ is the optimal load ratio of the network. The total transmission consumption for the request is no more than βL.

Proof: We first analyze the gap between the approximation solution and the optimal solution. In Find_Routing_path, the invariant $LB \leq \theta \leq UB$ always holds. When the algorithm terminates, $(UB - LB) \leq \epsilon$ holds, then, $LB \geq UB - \epsilon$. Thus, combined with the invariant, $UB - \epsilon \leq \theta \leq UB$, while $UB \geq \theta^*$ following the assumption. Thus, $\theta \geq UB - \epsilon \geq \theta^* - \epsilon$.

We then analyze the running time of Find_Routing_path. It is obvious that at each execution of the while loop, a single source shortest path tree rooted at s is constructed, which takes $O(m + n\log n)$ time when an efficient implementation of Dijkstra's algorithm [9] is employed, where m is the number of edges and n is the number of mobile hosts in the ad hoc wireless network. There are at most $\lceil\log(\frac{1}{\theta_{\max} - \theta_{\min}})\rceil$ iterations of the while loop. Therefore, the algorithm takes $O((m + n\log n)\log(\frac{1}{\theta_{\max} - \theta_{\min}}))$ time. ■

Note that the exact solution θ^* can be found if all links information of the residual network are available, which is expressed as follows. The number of iterations of the while loop in Find_Routing_path then is $O(\log m) = O(\log n)$ by sorting the load ratios associated with links in the residual network and finding next θ using the binary search in the sorted link sequence.

Thus, the algorithm takes $O((m + n \log n) \log n)$ time, which matches the time complexity of an algorithm given in [3]. However, collecting the information associated with all links in the residual network and performing sorting in an ad hoc wireless network takes lots of time and power consumption, which is against our initial goal to reduce the energy consumption for the routing. So, an approximation solution may be better off than an exact solution in terms of power conservation and extending the network lifetime.

B. Improved approximation algorithm

It can be seen that the number of iterations is $\lceil \log(\frac{1}{\theta_{\max} - \theta_{\min}}) \rceil$ in the `while` loop of `Find_Routing_path`, which determines the time complexity of the proposed algorithm. Using a square root approach [12], the running time of the proposed algorithm can be further improved through the reduction of the number of iterations in the `while` loop.

Since $0 < LB < \theta < UB \leq 1$, the next θ in `Find_Routing_path` can be found using a square root approach instead of using the binary search. Thus, a faster approximation algorithm for the relaxation of the original problem is described as follows.

```
Find_fast_path(G_r, ε)
    LB ← ε; /* the lower bound of θ */
    UB ← 1; /* the upper bound of θ */
    while   LB/UB < (1 − ε) do
            θ ← √(LB × UB);
            if    TEST(G_r, θ, β)
                  then   LB ← θ;
                  else   UB ← θ;
            endif
    endwhile.
```

If $LB \geq (1 - \epsilon)UB$, the `while` loop in `Find_fast_path` terminates immediately, and the solution obtained is at least $(1-\epsilon)$ times of the optimum due to that $\theta \geq LB \geq (1-\epsilon)UB > (1-\epsilon)\theta^*$. To speed up finding next θ in `Find_fast_path`, let $\frac{\theta}{LB} = \frac{UB}{\theta}$, which implies that $\theta = \sqrt{LB \times UB}$. Thus, the number of iterations of the `while` loop is $O(\log\log(\frac{1}{\theta_{\max} - \theta_{\min}}))$, which is almost constant for most practical cases. Thus, we have the following theorem.

Theorem 2: There is an approximation algorithm which delivers a feasible solution for the problem. The solution is no less than $(1 - \epsilon)\theta^*$. The algorithm takes $O((m + n \log n) \log\log(\frac{1}{\theta_{\max} - \theta_{\min}}))$ time, where $0 < \epsilon < 1$ is a small constant, $\theta_{\min} = \epsilon$, $\theta_{\max} = 1$, θ^* is the optimal load ratio of the network with the restriction that the total power consumption for the found routing path is no more than βL, and $\theta^* = \max_{v \in V}\{\theta(v)\}$.

Proof: From the above discussion, we know that the approximation solution delivered by `Find_fast_path` is at least $(1 - \epsilon)$ times of the optimum.

We now analyze the running time of `Find_fast_path`. It is obvious that at each execution of the `while` loop, a single source shortest path tree rooted at s is constructed, which takes $O(m + n \log n)$ time when an efficient implementation of Dijkstra's algorithm [9] is employed, where m is the number of edges and n is the number of mobile nodes in the ad hoc wireless network. There are at most $\lceil \log\log(\frac{1}{\theta_{\max} - \theta_{\min}}) \rceil$ of iterations of the `while` loop. Therefore, the algorithm takes $O((m + n \log n) \log\log(\frac{1}{\theta_{\max} - \theta_{\min}}))$ time. ■

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Remark: Both approximation solutions imply that finding a feasible solution for the problem is a complicated issue. It takes longer running time and consumes larger amount of energy to find an approximation solution within an additive factor of the optimal solution, whereas it takes less running time and consumes less amount of energy to find an approximation solution within a multiplicative factor of the optimal solution.

C. The distributed implementation

The algorithm given in [3] is inapplicable in a distributed environment, because it needs to collect the information of all links in the residual energy network and sorting the weights of links in order to find next θ for testing. The collection and sorting operations take lot of running time and consume lots of power energy of the network, which may defeat our original objective which aims to conserve the network energy. In contrast to theirs, in this paper our proposed algorithms can be implemented in the distributed environment easily. In the following we provide distributed implementations of the proposed algorithms.

In a distributed environment we assume that each mobile node is only able to contact its neighboring mobile nodes and knows who is its neighbors as well the links information between the mobile node and its neighbors. Also, each mobile node has the limited ability to perform some simple processing. We also assume that a distributed algorithm (Dijkstra's algorithm or Bellman-Ford's algorithm) for finding a single shortest path in an ad hoc wireless network is available. For the sake of simplicity, we here only consider the distributed implementation of algorithm `Find_fast_path`, the implementation of `Find_Routing_path` can be dealt similarly, and omitted.

Assume that the given ϵ, LB and UB are stored in the source node s initially. We first run a distributed algorithm for finding a single source shortest path from s to t in G_r to find the length L of the shortest path from s to t. The value of L is stored at node s too.

The outcome of each execution of the `while` loop body is a shortest tree rooted at s, and t is included in the tree. Once t is included in the tree, the source s is acknowledged through the found path, and node s then determines whether $\frac{LB}{UB} < (1-\epsilon)$. If not, the distributed algorithm for finding a single source shortest path started from s will be run again, using a different θ. Finally, a feasible solution (a routing path) can be found. The number of iterations of the `while` loop is $\lceil \log\log \frac{1}{\theta_{\max}-\theta_{\min}} \rceil$. In practice, $\lceil \log\log \frac{1}{\theta_{\max}-\theta_{\min}} \rceil$ is a small constant, and the approximation solution obtained is no less than $(1-\epsilon)\theta^*$, where θ^* is the optimal load ratio of the network.

IV. A Routing Algorithm for Heterogeneous Mobiles

In the previous section we assume all the mobile nodes in the network are equipped with the same type batteries, therefore, these batteries have the same capacities initially. The proposed algorithm is to maximize the load ratios of energy capacities of mobile batteries in the routing path. If the mobile nodes in an ad hoc network are equipped with different types of batteries, then the above algorithms may not be able to prolong the lifetime of a node as well the entire network. The reason behind is that, if applying the above proposed routing algorithms, the mobile nodes with larger battery capacities may still have plenty power energy left after realizing routings for a certain number of communication requests, whereas the mobile nodes with smaller battery capacities may have drained out whole their energy already, because each mobile node in the routing path reduces its transmission energy at the same rate without taking into account of its original capacity. To overcome this drawback incurred by the heterogeneity of the batteries, we propose the following algorithm which takes the heterogeneity of mobiles into consideration.

Suppose that every mobile node in the ad hoc network is equipped with one of K different energy capacities of batteries, and let $C_1, C_2, \ldots, C_k$ be the battery capacities. The basic idea of the proposed algorithm is to choose an energy capacity C as the *base energy capacity* of the network. That is, during choosing a routing path, the power energy consumption rates for those mobile nodes with smaller energy capacities ($C_p < C$) in the routing path are slower than that of those mobile nodes with base capacities. Similarly, the power energy consumption rates for those mobile nodes with the higher energy capacities ($C_q > C$) in the routing path are faster than that of the base capacity mobile nodes. As results, smaller energy capacity mobile nodes will have higher remaining energy capacities left, and larger energy capacity mobile nodes will have lower remaining energy capacities left, compared with the base energy capacity mobile nodes.

Define the *relative energy factor* rc_i between the base energy capacity C and the energy capacity C_i of mobile v_i as follows.

$$rc_i \quad = \quad \frac{C}{C_i} \tag{8}$$

Thus, for a smaller capacity mobile node v, we have $c_v > 1$; while for a larger capacity mobile node v, we have $0 < c_v < 1$. Assume that a mobile node v_i with capacity C_i in a routing path and link $\langle v_i, v_j \rangle$ in the path, define the *weighted capacity load ratio* $\theta_{i,j}$ of a link $\langle v_i, v_j \rangle$ as

$$\theta_{i,j} \quad = \quad \frac{p(v_i) - ke_{i,j}}{rc_i C(v_i)}, \tag{9}$$

and the *weighted load ratio of the network* as

$$\theta \quad = \quad \max_{\langle v_i, v_j \rangle \in E_r} \{\theta_{i,j}\} \tag{10}$$

For a mobile node u with the base energy capacity C, then $rc_u C(u) = C(u) = C$; for a mobile node u with a smaller or larger energy capacity $C(u)$, then $rc_u C(u) = \frac{C}{C(u)} C(u) = C$.

The following algorithm called *weighted capacity power aware routing* algorithm aims to find a routing path that maximizes θ and bounds the total transmission energy consumption in the path, which is described in Fig. 1.

In the above routing, we have seen that the mobile nodes with different battery capacities have different transmission energy reduction rates. With the time progress, the remaining energy capacities of either smaller or larger energy capacity mobile nodes

```
Gen_TEST(G_r, θ, β, C)
find a shortest path in G_r from s to t, let L be
the length of the path.
if   no such path exists,
     then   there is no routing path for the request.
            exit;
     else   /* find a routing path */
          g_s ← 0;
          parent(s) ← s
          for    all v ∈ V − {s}   do
                 g_v ← ∞;
          endfor;
          for    all v ∈ V   do
                 rc_v ← C / C(v);
          endfor;
          for    i ← 1 to n − 1   do
                 for   each ⟨u, v⟩ ∈ E_r   do
                       if   ((p(u) − k e^α_{u,v}) / (rc_u C(u)) ≥ θ)&
                            (g_v ≥ g_u + k e^α_{u,v})
                            then   g_v ← g_u + k e^α_{u,v};
                                   parent(v) ← u
                       endif;
                 endfor;
          endfor;
          if     g_t > βL
                 then   return   false;
                 else   return   true;
          endif;
endif.
```

Fig. 1. A Weighted Capacity Power Routing Algorithm

will approach to the level of the base energy capacity mobile nodes in the end. Then, the function of algorithm `Gen_TEST` is identical to that of algorithm `TEST` when all mobiles have the same remaining energy capacities. Having `Gen_TEST`, a maximal θ is found easily by invoking either `Find_Routing_path` or `Find_fast_path`, depending on how to tradeoff the running time and the accuracy of the approximation solution obtained.

So far we have assumed that the base energy capacity C is given. In practice, choosing a good base energy capacity C is an important issue because the choice of C will determine whether or not the lifetime of the network can be prolonged indeed. How much energy contributed for the choice is also needed to be addressed. In the following we provide an approach to choose a good base energy capacity C.

If there is one energy capacity C_i battery among the K different capacities of batteries, which is equipped by the majority of mobile nodes (at least half of mobile nodes) in the network, it will be chosen as the base energy capacity $C = C_i$ automatically. This observation is, if there are only a few mobile nodes having the base energy capacity C_i in the network, then this choice is not good because the routing algorithm may not be able to find a routing path for a communication request, despite that the majority of mobile nodes in the network have sufficient energy left. The heuristic to choose a base energy capacity based on the majority of mobile nodes favors maintaining the network connectivity by maximizing the remaining energy capacities of the mobile nodes with the base energy capacity.

If no majority of mobile nodes are equipped with a single energy capacity C_i in the network, $1 \leq i \leq K$, the base energy capacity is chosen as follows.

Let n_j be the number of mobile nodes with energy capacity C_{i_j} in the network, $1 \leq j \leq K$, $1 \leq i_j \leq K$. Assume that $n_1 \geq n_2 \geq \ldots \geq n_K$. Let l be the smallest integer such that $\sum_{j=1}^{l} n_j \geq n/2$. Then, the base energy capacity is chosen

$$C = \frac{\sum_{j=1}^{l} C_{i_j}}{l}. \tag{11}$$

Finding the base energy capacity C, however, takes time and energy overhead consumption. Following the assumption that K is a small constant, it does not take much time and consume much energy to find it, and C can be found in a distributed environment as follows. Choose a mobile node as the source, and broadcast each different energy capacity from the source to other mobile nodes in the network. Each mobile node then acknowledges whether it is equipped with the broadcasting energy capacity. The source finally proceeds the census. Having collected the K energy capacity values, the source performs sorting of the K values in decreasing order and choose one type of battery capacity as the base capacity, and broadcasts the base energy capacity to all the other mobile nodes. Note that the computation of the base energy capacity in the network is only carried out once, which is worthwhile for saving the entire energy of the ad hoc wireless network.

V. Conclusions

In this paper we have proposed power-aware routing protocols in an ad hoc wireless network to prolong the lifetime of the network. Our investigation reveals that optimizing both the power consumption at each mobile node and the total transmission power consumption at a routing path for each request is quite challenging. A tradeoff between these two conflict optimization objectives is needed, and the proposed algorithms balance these two objectives very well.

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