A Local Decision Algorithm for Maximum Lifetime in Ad Hoc Networks

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Abstract. Mobile hosts of ad-hoc networks operate on battery, hence optimization of system lifetime, intended as maximization of the time until the first host drains-out its battery, is an important issue. Some routing algorithms have already been proposed, that require the knowledge of the future behavior of the system, and/or complex routing information. We propose a novel routing algorithm that allows each host to locally select the next routing hop, having only immediate neighbor information, to optimize the system lifetime. Simulation results of runs performed in different scenarios are finally shown.

1 Introduction

An ad hoc network is a collection of wireless hosts forming a temporary network without the aid of any centralized administration. It can be mobile, with more or less frequent topology changes over time, or static, such as sensor based monitoring network. Hosts communicate establishing multi-hop paths by means of a route discovery algorithm, usually based on the flooding mechanism.

The routing is maintained in a route cache by each wireless host, until the destination is reachable. If not, the route discovery algorithm is again started.

A host can be no more reachable either in a mobile or in a static network: some host of the route could move, falling outside the transmission range of the sender, or the signal propagation conditions could change.

Different route discovery algorithms have been proposed in literature, depending on the knowledge of the network (e.g. host positioning and link congestion), on the selected metric and on the possibility of adjusting the transmission energy level. A short selection follows.

In [1] the shortest-path routing in hops number is selected, considering fixed transmission energy, in [2] the route discovery is optimized, having information about the positioning and the mobility of the host. The aim of these algorithms is to minimize the energy consumed in routing a data packed. The same problem has been addressed in [3] and [4], but considering adjustable transmission power. In this case, an approximation of the MINIMUM PATH ENERGY GRAPH is considered.

Minimum energy paths finding is not the unique metric considered: for example in [5] the route selection metric is the host routing load. The path is reconstructed when intermediate hosts of the route have their interface queue overloaded. In [6] the objective is to maximize the system lifetime, defined as the time until the first host battery drain-out, when the rate at which each information is generated at every host is known, and transmission energy can be adjusted.

In [7] a similar approach is proposed, considering as metric the remaining battery capacity of each node: nodes with low capacity have some "reluctance" to forward packets, and such a reluctance is taken in account in the cost function definition for the routing algorithm. No previous knowledge of the information generation rate is required. However, it is necessary to evaluate alternative routes for each destination and to know the minimum value of the battery capacities, dynamically changing, of the hosts belonging to each route.

In this paper we refer to battery operating devices, with adjustable transmission energy, arranged either in static or in mobile networks with few topology changes over time, where it is possible to reason as the network is static for most of the time. Our objective is to study how to prolong the system life time, as defined in [6], but without a-priory knowledge of the information rate generation, using a limited amount of information at each node, and without calculating (or recalculating) alternative paths for each pair of source-destination.

The starting point has been the analysis of the influence of the path selection on the path cost. Selecting an alternative path with respect to the better one could have the advantage of resulting in a more uniform energy consumption, and probably also in a better load balancing, but could lead to a higher global energy consumption, with negative effects on overall routing. In fact, the goal of optimizing different metrics is not always reachable.

Then, instead of considering how each node could split incoming traffic among different paths, we define a novel decision algorithm that allows each node to locally select the next relay node, having only the knowledge of the remaining battery capacity of the neighbor hosts falling in its radio coverage range.

This algorithm, called ME+LS, has been at the moment studied and simulated only considering the power consumption for the routing.

It can be applied as "additional selection level" starting from an already existing route discovery algorithm that minimizes the path energy, such as the one presented in [4]. Some additional information must be transmitted and recorded during the route discovery and the data transmission.

2 The Network Model

In wireless network minimization of power consumption is an important requirement

Radio transmission between two devices at distance *d* requires power consumption proportional to d^n : usually *n*, the path-loss exponent of outdoor radio propagation, assumes a value out of 2, 3 or 4. We will consider only transmission power, the most important parameter to determine the energetic balance, ignoring receiving power (always constant, independently from the position of the sending device) and computational power consumption, since usually communication costs are more expensive than the others.

Given a network *N* of wireless devices, let us consider the complete weighted graph $G=(V, E)$ where *V* is the set of nodes, each one corresponding to a device, and *E* is the set of bi-directional edges (u, v), for each $u, v \in V$. The weight *w* of an edge *e*, that is $w(e)$, is the transmission cost of a single data packet over that link, that is:

$$w(e) = c \, | (u, v) |^{n} . \qquad (1)$$

for some *n* and constant *c*. Supposing W_{max} be the maximum power value at which a node can transmit, we delete from *G* all the edges having weight greater than W_{max}. The graph *G* so obtained is called *Reachability Graph* (*RG*), the edges of which represent a transmission link between the edge end points. Considering the *RG* of a network, a *route* between two nodes n_1 and n_k is a paths $P = (n_1, n_2, \ldots n_k)$ over *RG*, the cost of which is defined as:

$$C(P) = \Sigma_{i} \, w ((n_{i-1}, n_i)) . \qquad (2)$$

for every $n_i \in P$. The cost of a route is also the total power consumption required to transmit a data packet from the host n_1 to the host n_k .

Finally, the Minimum Energy (*ME*) route between two nodes is the path linking the two nodes having the minimum cost. Actually, two hosts apparently linked in the *RG* could not to communicate because of obstacles that prevent the communication. In this case, additional edges can be removed from *RG*, without deteriorating our results.

The sub-graph of *RG* including all and only the edges belonging to some Minimum Energy path is called *Minimum Energy Reachability Graph (MERG)* for the network *N*. *ME* routes guarantee the minimization of the total power consumption, since they allow the transmission of a message with the lower power cost.

3 Pros and Cons of Minimum Energy Reachability Graph

Distributed algorithms that build approximations of *MERG* for a network, generally use local decisions that however guarantee some global optimization. They start with every node sending a beacon at the maximum power, or growing it transmission power, until it finds neighbor hosts satisfying a predetermined property and ensuring the connectivity of the network.

*MERG*s have also another advantageous property: the low cost of the edges (then the low transmission power) and the small node degree ensure a minimal interference and allow a high throughput.

However, they also have a critical disadvantage: due to the limited node degree, and consequently, the low number of edges and paths of the *MERG*, some host maybe part of an increasing number of routes. This fact leads to a quick consumption of its battery capacity. Power consumption thus depends from such the degree of a host and from the energy that it must consume to forward a packet to the next relay host. The hosts that behave like collectors of route branches and like bridges to far hosts are candidates to faster drain-out their batteries.

This situation is likely to occur when the message traffic is mainly in the form of many-to-one, such as in sensor networks where information flows to a Base Station, or in a mobile environment where communications are directed to a coordinator. In these cases, the resulting network topology is a spanning tree that leads to highly non-uniform energy utilization and concentrates routes in few nodes.

The problem of maximizing the network lifetime is equivalent to solve a linear programming problem to find the maximum flow, under the flow conservation condition, and supposing to know the set of origin nodes and the set of destination nodes for each commodity, and the rate at which information is generated at every node belonging to some commodity. Building in a distributed way the solution of this problem could be heavy in energy consumption, if the network is not static, and it is not useful when the dynamic of the information generation is not known a priori.

4 The ME + Link Selection Algorithm

Our algorithm may inherit one already existing *MERG* approximation and routing discovery algorithm and extends it by adding a Link Selection strategy during transmission operation to prevent, at some extent, early energy consumption in critical nodes. Link Selection requires that some values be piggybacked with messages and aks during the transmission. It is useful to distinguish two different phases: a set-up phase (routing discovery), and the message transmission phase.

4.1 Set up for Link Selection

Let us start considering a generic existing algorithm that finds an approximation of the *MERG* during the route discovery phase (hereafter called the basic algorithm).

During this phase, a host **a** collects information about the hosts within its transmission radius. With respect to **a** there are two kinds of hosts: those that are its *neighbors* in the approximated *MERG*, composing the set *H(**a**)*, and those that are *reachable* (that is, which are neighbors of **a** in the *RG*) but that are not neighbors in the *MERG*, composing the set *R(**a**)* .

The ME+LS algorithm requires each host to transmit few additional information together with the control messages needed for the basic algorithm:

1. Each node must know not only the first hop host of the route to a destination, but also the second one,
2. Each node transmits (with the maximum energy possible with respect to the basic algorithm) its *R* set.

The meaning of this additional information is represented in Fig. 1. The circle represents the maximum communication radius of host **a** allowed by the basic algorithm, solid lines represent the edges belonging to the approximated *MERG*, dashed lines represent edges in *RG* not in *MERG* and dotted lines represent possible multi hops paths to the destination hosts **A**, **B** and **C**. Host **a** knows that **d**, **f** and **g** are the second relay hosts on the path to, respectively, **A**, **B** and **C** (from point 1 above). Moreover, **a** also knows that **f** is reachable from **e** (from point 2 above).

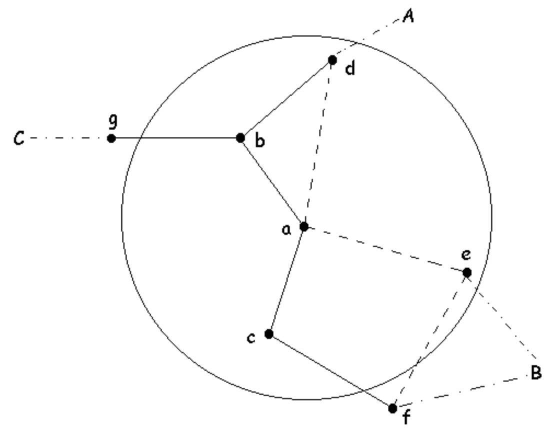

Fig. 1. Environmental knowledge of a host **a**

As an example, to route a message from **a** to the destination **A**, the host **d** is the next hop host after **b**, and **d** can be reached directly from **a**, even if with a greater energy consumption. Considering destination **B**, **f** is the next hop host after **c** and, even if not directly reachable from **a**, it can be reached by **a** through **e**. However, a message routed through **e** to reach the destination **B**, could not to follow the same path as it was routed through **f**, since a different path could be selected by **e**.

Path (**a**, **d**) is called *diagonal alternative path* from **a** to **d**, while path (**a**, **e**, **f**) is called *triangular alternative path* from **a** to **f**.

4.2 Transmission phase with Link Selection

The Link Selection algorithm acts when the devices are transmitting and routes are effective.

Link Selection algorithm requires that when a host forwards a message or an ack, it also piggybacks its remaining battery level. Considering some host **a**, it can receive this additional information from hosts in *R(a)*, provided that the transmitting radius used for this communication is sufficiently large. Link Selection is a symmetric algorithm acting as follows during the message forwarding:

Algorithm Transmission with Link Selection:
// for host **a**

```
begin
   when a message arrive at host a to be routed to destination A:
           Look in the routing table for destination A, finding a path having
                   host x as first hop and host y as second hop;
           Compare residual battery energy (rbe) of the hosts:
           case rbe (a) <= rbe (x) :
                   send message to x;
                   exit;
           case rbe (a) > rbe (x):
                   // look for a diagonal or triangular path connecting a to y
                   if a diagonal path exists then
                           send message to y,
                           exit;
                   if a triangular path (a, z, y) exists then
                           if rbe (z) <= rbe (x),  then
                                   send message to x;
                                   exit;
                           if rbe (z) > rbe (x) then
                                   send message to z;
                                   exit;
                    send message to x   // no alternative path found
end
```

Referring to Fig. 1, if a message has to be forwarded to destination **A**, a diagonal alternative path can be considered; if the destination is **B** a triangular alternative path would have been taken in account, through host **e**. No alternative paths exist to destination **C**. If battery consumption for some host in *R* is not known, an approximated value can be considered as for example a weighted average, to be updated after the receipt of the ack for a message routed through it.

Roughly, the ME+LS algorithm tries to limit the energy consumption of the ME path hosts, using alternative paths.

It is worthwhile to put in evidence that the presented algorithm has two nice properties:

1. It exhibits an adaptive behavior so that, if the communication pattern changes (e.g. in case of temporary clusters), the selected paths are modified in order to better use the energy of nodes with the largest availability;
2. It is based on a local decision criteria thus requiring for each node to maintain only a limited amount of information, more precisely a table with the first 2 hosts for each ME path.

As it will be discussed in the following Section, simulation results show that the algorithm provides, on the average, good results but with some variance. It is possible to look for improvements considering at least the following aspects:

– If we have information about relative node positions then we may refine the criteria to select between diagonal and triangular alternative paths;
– A threshold difference between the residual battery energy of two hosts could be considered, instead to evaluate only the simple difference;
– Additional information could be transmitted by the acks, for example the minimum residual battery energy of the path.

5 Simulation Results

In this simulation, we considered only the transmission phase, considering static networks, since the power consumption during message exchange is prevailing in network having few topological changes over time. For these reasons, we do use any particular *MERG* approximated evaluation and routing discovery algorithm, but instead we base simulation on the actual Minimum Energy Path graph, building it by means of the Bellman Ford algorithm. Again to not depend on any particular set-up algorithm, the alternative links considered in the *ME+LS* algorithm are Delaunay edges that approximate the possible environmental knowledge of each host.

*MERG*s have been generated considering 50, 100 and 150 nodes placed randomly within a 1500*m* x *1500m* area, with radio propagation range for each host of 450*m*. in order to simulate different densities. For each different number of hosts, 300 runs have been conducted, and finally the data collected have been averaged.

To investigate the impact of our algorithm, we also considered two completely different communication scenarios.

– *Scenario A*: many-to-one communication to a unique sink host, like in sensor networks where devices send information to a Base Station or in mobile networks where hosts send messages to a fixed installation.
– *Scenario B*: a completely random communication scheme, where hosts communicate with each other. Such an environment is not realistic, but it is useful to test the algorithm in an extreme situation.

Finally, with respect to formula (1) , we performed simulations using two values of *n*, that is *n=2* and *n=4*. Performances obtained with the ME+*LS* algorithm have thus been compared with the results obtained using only minimum energy paths, and also using the minimum hop path, with the maximum transmission energy for each host. All the hosts had the same initial energy, but different for each value of *n*.

As an example, let us consider a single trial, with 100 hosts randomly distributed, sending information to a sink host and outdoor radio propagation *n=2*. Fig. 2. (a) shows the minimum energy paths built over the *MERG*, while Fig. 2. (b) shows the Delaunay graph. Fig. 3 shows the *ME+LS* paths graph, obtained after the simulation.

The final energy distributions have been evaluated.

Nodes labeled with letter **a** terminated the simulation with less than 1/6 of the initial battery energy, with letter **b** if the final energy is less than 1/3 of the initial, with letter **c** less than 1/2 and letter **d** less than 2/3.

Transmitting over the *MERG*, the host labeled with **a** drains-out the battery after that 1299 messages have been received from the Base Station, while using the *ME+LS* algorithm 2488 messages are received.

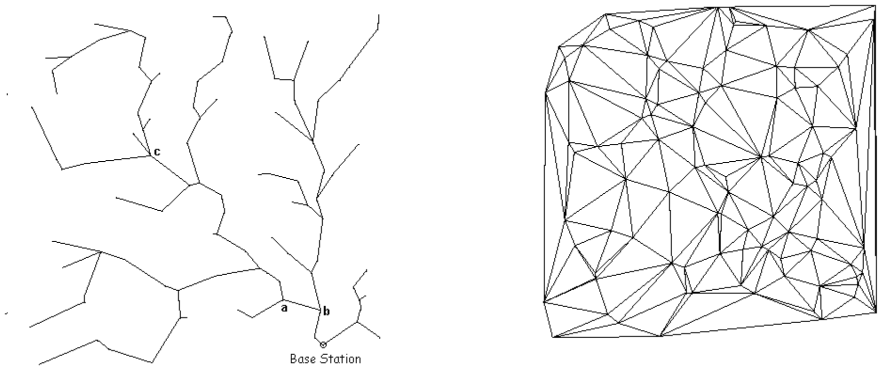

Fig. 2. (a) Minimum energy path graph (on the left) and (b) Delaunay graph (on the right)

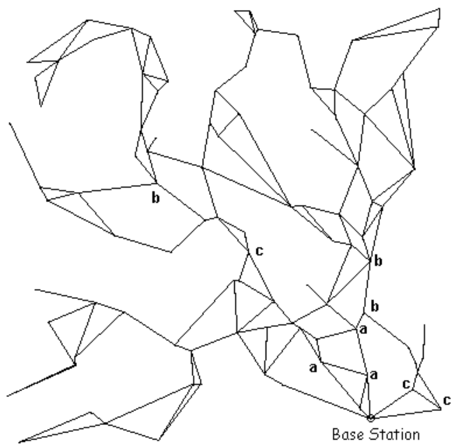

Fig. 3. Paths followed by packets using the MERG+LS algorithm

Using *n=4*, the Base Station receives 1081 messages in the first case, 1873 in the second case. In this last trial, on a total of 21601 hops, 2208 of them have been made using diagonal alternatives and 2340 with triangular alternatives.

Remark that diagonal hops allow bypassing hosts with low battery energy, but require higher energy consumption from sending hosts. Triangular hops sometimes allow jumping on a different branch, leading to more uniform energy consumption.

Looking at Fig. 3, the branch on the right, composed by 7 hosts, routes to the Base Station part of the data that otherwise would be flowed over the branches on the left.

In Tables 1 and 2 the results of the simulations are shown as follows: in *ME* columns the results obtained routing data through *ME* paths (that is, the average number of messages sent before the first host drain-out its battery), in *MH* columns the results obtained using the minimum hop routing algorithm, in *LS* columns the results obtained running the *MERG+LS* algorithm, and finally, in columns *%* the percentage difference between column ME and column LS.

Table 1 shows results of the simulation of scenario A, considering on the left *n=2*, on the right *n=4*. The same for Table 2, but with respect to scenario B.

Table 1. Scenario A: columns on the left show results obtained with a path-loss exponent of outdoor radio propagation n=2, with n=4 on the right

Nodes	ME	MH	LS	%	ME	MH	LS	%
50	1050	677	1390	32	679	88	839	23
100	1849	508	2470	33	2140	111	2621	22
150	3056	530	4124	35	5614	113	6976	24

Table 2. Scenario B: columns on the left show results obtained with a path-loss exponent of outdoor radio propagation n=2, with n=4 on the right

Nodes	ME	MH	LS	%	ME	MH	LS	%
50	3042	999	3645	20	835	102	879	5
100	7370	1386	9183	24	3896	153	3983	2
150	12208	1596	15337	25	9798	176	9887	1

The three different distributions show similar results: in fact, the average out-degrees of the ME and ME+LS routing graphs of Scenario A are respectively: 4.20 and 4.93 for 50 nodes, 4.41 and 5.49 for 100 nodes, 4.46 and 5.66 for 150 nodes. That is, the different density leads to a little increase of the number of outcoming edges per node, and, consequently, to a related performance improvement.

A final remark can be made: the routing performed using only the ME graph is not sufficient to guarantee the maximization of the system lifetime. In fact, in Scenario A the minimum energy path graph is a spanning tree, thus the hosts behaving as collector of branches risk to run down very quickly. In this case *ME+LS* algorithm performs well, since it is possible to bypass overloaded hosts, increasing the power consumption of non-critical hosts.

However, in Scenario B, with random paths, the energy is consumed in a more uniform way. In this case alternative routings, consuming more energy, are not always convenient, at least when *n* is greater than 2, because the selection of a non minimum weight alternative path has a very high impact on the total energy consumption.

This consideration confirms the fact that the two goals, minimize the total transmission power and maximize the system lifetime, cannot be reached simultaneously when the characteristics of the network are not known in advance.

However, the *ME+LS* algorithm significantly improves the system lifetime when some kind of organization is present in the network, for example when some hosts are more important than the others, being fixed installations or cluster coordinators. Moreover, one promising approach in dealing with the obstacle above stated, may be to have a host choose an alternative path only if some threshold in the remaining battery energy difference has been overcome.

Given the encouraging results, our future work will be to perform simulations of the complete algorithm also considering the threshold correction.

6 Conclusion

The route selection mechanisms based on minimum energy paths do not guarantee the maximum system lifetime and can lead to network congestion, since the routing load is likely to be concentrated on certain nodes. The *MERG+LS* helps to prolong the system lifetime and, selecting alternative paths, to better balance the load.

It could also give higher stability to a route: for example a device could temporally be unable to relay data packets due to changed signal propagation conditions, or signal interference. The possibility of selecting different local routing before to run the route discovery algorithm, at least for some time, increases the longevity of the routes. In this manner, the routes are likely to be long-lived and hence there is no need to restart frequently, resulting in higher attainable throughput.

Finally, *ME+LS* algorithm benefits of the fact that it uses only immediate neighbor information in selecting the alternative routing, thus requiring limited amount of memory.

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