Energy-Aware Routing in Wireless Ad-hoc Networks

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Abstract

In this work we study energy efficient routing strategies for wireless ad-hoc networks. In this kind of networks, energy is a scarce resource and its conservation and efficient use is a major issue. Our strategy follows the multi-cost routing approach, according to which a cost vector of various parameters is assigned to each link. The parameters of interest are the number of hops on a path, and the residual energy and the transmission power of the nodes on the path. These parameters are combined in various optimization functions, corresponding to different routing algorithms, for selecting the optimal path. We evaluate the routing algorithms proposed in a number of scenarios, with respect to energy consumption, throughput and other performance parameters of interest. From the experiments conducted we conclude that routing algorithms that take into account energy related parameters, increase the lifetime of the network, while achieving better performance than other approaches, such as minimum hop routing.

1 Introduction

In this work we study energy efficient routing strategies for wireless ad hoc networks. The nodes of an adhoc network are battery-operated and recharging or replacing the battery is usually not easy or feasible. As a result, energy is a scarce resource and limits the performance and lifetime of the network. Generally, a node participating in an ad-hoc network, consumes energy when transmitting, receiving or processing data, or when simply listening to the channel.

Many routing protocols compute the optimal paths based only on minimizing the hop-count. In such protocols some nodes may end up forwarding considerably more traffic than other nodes and may soon run out of energy. As a result the network may get disconnected, even though many nodes with sufficient energy still exist. Even when the network does not get disconnected, the lack of sufficient energy at some nodes may force future packets to take very long paths limiting performance. It is therefore important for the routing algorithms, when selecting the paths, to take into account, in addition to the number of hops, various energy-related parameters, such as the transmission power and the residual energy of the nodes. The goal is to make the network operational for as long as possible before it gets partitioned, by increasing the lifetime of the nodes.

We can distinguish between two routing approaches: the single-cost and the multi-cost approach. Most routing protocols proposed to date, are based on the single-cost idea, where a single metric is used to represent the cost of using a network link. This link metric can be a function of several network parameters but it is usually a scalar. Routing algorithms of this kind calculate the path with the minimum cost for each source-destination pair.

Single-cost routing algorithms cannot support differentiation of service for sessions with varied QoS requirements. They also limit the set of optimization functions that can be used for selecting the paths. Another drawback of these algorithms is that they usually select only one path for each source-destination pair, leading to non-uniform traffic distribution and other oscillation problems.

In multi-cost routing, a cost vector consisting of various cost parameters is assigned to each link, whose elements are considered separately until the very end, when the cost vectors of the candidate paths are calculated. According to an optimization function the optimal of these paths is finally selected.

Various experiments studying the network performance under different optimization functions were con-

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ducted. We find that by using appropriate energy-based cost functions, energy consumption can be spread more evenly in the network, leading to longer lifetime for the network nodes. Even though energy-aware routing often tends to use longer paths than the minimum required, it is observed that in the long run, when nodes start running out of energy, it gives better performance results.

The remainder of the paper is organized as follows. In Section 2 we present an overview of previous work on energy-efficient routing. In Section 3 multi-cost routing is discussed. In Section 4 we discuss energy-aware routing algorithms that are based on the multi-cost routing approach. In Sections 5 and 6 we describe and discuss the results of the experiments. Finally in Section 7 we present our conclusions.

2 Previous Research

Relatively recently the design of energy efficient routing protocols for wireless ad-hoc networks evolved as a main research topic, and several energy-aware routing protocols were proposed[1][5]. Some protocols use the transmission power, the residual energy or combinations of them as metrics in the selection of energy efficient paths[6][7][3]. Other works in doing so take into account the end-to-end probability of error, or the expected number of retransmissions for the reliable delivery of the packets. The selection and use of multiple energy efficient paths for the same source-destination pair has also been proposed[8]. Energy-efficient multicast and broadcast in ad-hoc networks has been studied in [9]. All the protocols mentioned above follow the single-cost approach. Despite the potential of multi-cost routing, the research activity on this field has not been intense. The idea of multi-cost routing was first presented in [2] where it was applied to wireline max-min fair share networks. The work in the present paper is, to the best of our knowledge, the first time that multi-cost routing is applied to the case of wireless networks.

3 Multi-cost Routing

In the multi-cost approach, each link of the network is assigned a cost vector that consists of several cost parameters. The cost vector of a path is obtained from the link cost vectors by applying, component-wise, a monotonic associative operator to each cost vector parameter.

A multi-cost routing algorithm consists of two phases. In the first phase, an enumeration of an appropriate set of candidate paths for a given source-destination pair is performed. In the second phase, the optimal path is chosen from this set according to an optimization function, which is applied to the parameters of each path's cost vector. A complete description of how multi-cost routing operates can be found at [2].

4 Energy-Aware Routing

In a wireless network, the power of the signal at a receiver, that is at distance d from the sender is $P_r(d) = \frac{P_t}{d^a}$, where P_t is the power of the transmitted signal. The parameter a is the path loss constant, and is typically between 2 and 4 depending on the wireless channel. In our experiments a was taken to be equal to 2.

4.1 Cost Metrics

The multi-cost routing algorithms we propose for energy aware routing in ad hoc networks use three cost metrics. The number of hops of a path (h), the residual energy at the transmitting node i of a link (i, j) (R_i) and the transmission power at the transmitting node i of a link (i, j) (T_i).

The number of hops h of a path is obtained by adding the links that belong to it. So, h is said to be an additive cost metric. Parameter R_i of a path represents the minimum residual energy left on the nodes of the path, so referred to as a restrictive cost metric. Finally, the parameter T_i of a path can be either the maximum or the sum of the transmsission powers of the path's nodes. In the former case we define T_i as a maximum representative, while in the latter as an additive cost metric.

4.2 Optimization Functions

The optimization functions, corresponding to different routing algorithms, studied in this work are listed below along with the criterion each of them optimizes.

- *Minimum-Hop*: $f = h$
- *MAX/MIN Energy*: $f = \frac{\max_{i \in P} T_i}{\min_{i \in P} R_i}$
- *SUM/MIN Energy*: $f = \frac{\sum_{i \in P} T_i}{\min_{i \in P} R_i}$
- *MAX/MIN Energy-Hop*: $f = h \times \frac{\max_{i \in P} T_i}{\min_{i \in P} R_i}$
- *SUM/MIN Energy-Hop*: $f = h \times \frac{\sum_{i \in P} T_i}{\min_{i \in P} R_i}$
- *MAX/MIN Energy-Half-Hop*: $f = \sqrt{h} \times \frac{\max_{i \in P} T_i}{\min_{i \in P} R_i}$
- *SUM/MIN Energy-Half-Hop*: $f = \sqrt{h} \times \frac{\sum_{i \in P} T_i}{\min_{i \in P} R_i}$

4.3 Implementation of the Algorithm

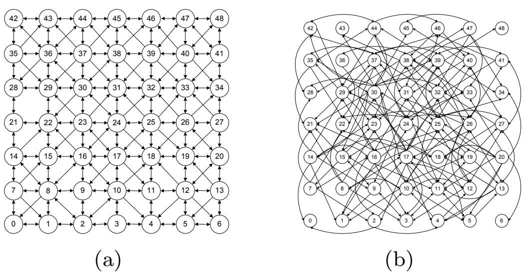
We implemented the proposed algorithms and carried out corresponding experiments using the Network Simulator[4]. The routing agent running on each node calculates the set of non-dominated paths towards all possible destinations at periodic time intervals. In our initial experiments we assumed that each node has global knowledge of the network topology and all other information it needs for making routing decisions.

Source routing is used at the nodes according to a QoS set of requirements, which specifies the optimization function to be used for the selection of the paths. When a data packet is generated at a node, the node applies the function to the cost vectors of the non-dominated paths to select the optimal path. If no route to the destination can be found, the packet is discarded.

5 Model used for performance analysis

The ad-hoc network consists of 49 stationary nodes connected in a 7×7 grid topology. The distance between the nodes is set at 50m. The MAC protocol we used is a slightly modified version of IEEE 802.11, where the maximum number of packet retransmissions due to collisions was taken to be practically infinite (equal to 2000 retransmissions).

The initial energy of the nodes is taken to be either 100 or 2 joules. The transmission range is either fixed at 50m, or it is varying from node to node (uniformly distributed between 50m-100m in one set of experiments, and between 50m-150m in another set of experiments). The topologies for the variable transmission range scenarios, are shown in Figure 1.



(a) (b)

Figure 1. Illustrates (a) Network topology when the transmission range of the nodes varies between 50m-100m and (b) Network topology when the transmission range of the nodes varies between in the range 50m-150m (we omit the edges that have already been shown in the previous topology figure).

The amount of energy expended at a node for a packet transmission is taken to be equal to its transmission power multiplied by the duration of the packet transmission. We assume that the energy consumed for the reception and the processing of a packet is constant and is the same for all nodes. More specifically, the energy expenditure for a packet reception at a node is taken to be equal to 10% of the transmission power required for the minimum transmission range (50m) multiplied by the packet duration. We assume that the processing energy cost of the packet is included in this energy expenditure. When a node is idle we assume that it consumes no energy.

The performance of the routing algorithms proposed was evaluated in the setting of the evacuation problem. In this problem, there is a fixed number of packets per node that have to be delivered to their destinations. In our experiments, the number of packets in the network varies from 100 to 1000 (at steps of 100) packets per node. Packet destinations are taken to be uniformly distributed over all remaining nodes of the network. The size of the packets is fixed at 500 bytes and the transmission rate is equal to 0.1packets/sec. The interval between non-dominated path recalculations is taken to be equal to 1 second.

6 Performance results

In the experiments conducted we measured the average residual energy E remaining at the nodes at the end of each experiment, the variance σ_E^2 of the node residual energies, the time when a node runs out of energy, referred to as the node Depletion Time (DT), the average number of hops $\overline{h}$ on the paths taken by the packets, the received-to-sent packets ratio (RS) and the number of collisions C between packets.

6.1 Energy related performance measures

The results of Figure 2 show that the *Minimum-Hop* algorithm results in a higher E at the end of the evacuation problem than the other routing algorithms examined. However, the *Minimum-Hop* algorithm also results in less uniform energy consumption in the network and a smaller depletion time than the other algorithms, as indicated by the results on the variance σ_E^2 and the depletion time DT shown in Figures 3 and 4 respectively.

These observations can be justified by looking into the way the algorithms considered operate. The *Minimum-Hop* algorithm selects and uses the same path for the entire duration of a session, or until the energy of a node on the path is depleted. As a result, only a small subset of nodes participate in the transmission of packets. The *Energy*[1] and *Energy-Hop*[2] optimization functions, however, are based on parameters (namely R_i) that change over time, and the path selected may not remain the same for all packets in the session. In this way the traffic is spread over a larger number of nodes, leading to smaller σ_E^2.

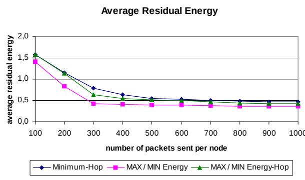


Figure 2. Illustrates the average residual energy at the end of the evacuation problem for the *Minimum-Hop*, *MAX/MIN Energy* and *MAX/MIN Energy-Hop* algorithms. The results were obtained for the case of finite energy and the topology of Figure 1a.

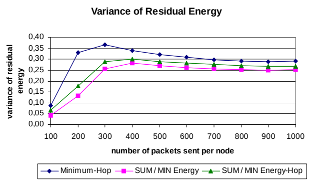
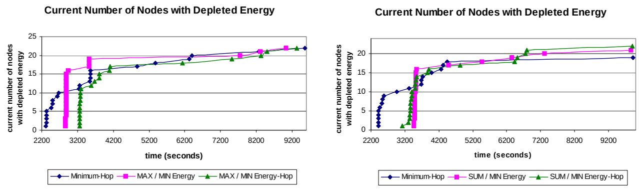


Figure 3. Illustrates the variance of the residual energy at the end of the evacuation problem for the *Minimum-Hop*, *SUM/MIN Energy* and *SUM/MIN Energy-Hop* algorithms. The results were obtained for the case of finite energy and the topology of Figure 1a.

Regarding the time the energy of the nodes is depleted, the *Energy-Hop* optimization functions exhibit the best performance in all the experiments, while the *Minimum-Hop* optimization function seems to result in the worst DT.

Another interesting observation regarding the results on the DT for the *Energy* and *Energy-Hop* algorithms, is that when most of the nodes start running out of energy, this happens almost simultaneously for all nodes. This is due to the uniform way both of these algorithms spread the energy consumption in the network, so that when one node is at the point of running out energy, most other nodes are at the same energy-critical situation.

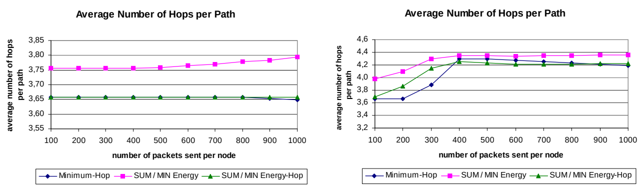


(a) (b)

Figure 4. Illustrates the current number of nodes with depleted energy during the experiments for the *Minimum-Hop* and (a) *MAX/MIN Energy*, *MAX/MIN Energy-Hop* and (b) *SUM/MIN Energy*, *SUM/MIN Energy-Hop* algorithms. The results were obtained for the case of finite energy and the topology of Figure 1a.

6.2 Network Performance related performance measures

The *Energy* and *Energy-Hop* algorithms, as expected, select and use paths that are longer than the minimum-hop paths, because they use the parameters R_i and T_i as cost metrics for the links. However, when the nodes have finite energy, there are cases where the *Energy-Hop* optimization function achieves smaller $\overline{h}$ (Figure 5). This happens because the *Minimum-Hop* algorithm has to eventually use longer paths when some of the nodes run out of energy.



(a) (b)

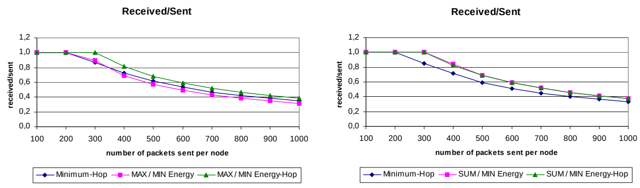
Figure 5. Illustrates the average number of hops of the paths followed for the *Minimum-Hop*, *SUM/MIN Energy* and *SUM/MIN Energy-Hop* algorithms. The results were obtained for the case of (a) infinite and (b) finite energy and the topology of Figure 1a

Regarding the received-to-sent packets ratio RS, when the initial energy of the nodes is assumed to be infinite, no nodes run out of energy and all the packets are delivered to their destination. When the initial energy is assumed to be finite, however, the *Energy-Hop* algorithms achieve the best results in almost all the experiments. The reason for this is that with these algorithms the network nodes remain alive for longer periods of time. The *MAX/MIN Energy* algorithm seems to give the worst results among the algorithms in this

[1] MAX/MIN Energy and SUM/MIN Energy algorithms are jointly referred to as the Energy algorithms.

[2] MAX/MIN Energy-Hop and SUM/MIN Energy-Hop algorithms are jointly referred to as the Energy-Hop algorithms.

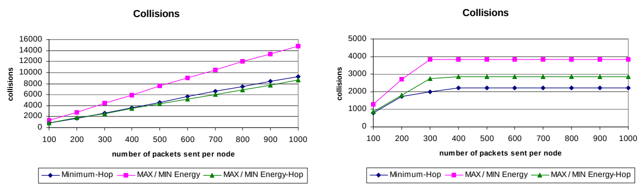
class. However the performance of the *SUM/MIN Energy* function is considerably better and it surpasses, even marginally, the *SUM/MIN Energy-Hop* optimization function (Figure 4).



(a) (b)

Figure 6. Illustrates the received received-to to-sent packets ratio for the *Minimum-Hop* and (a) *MAX/MIN Energy*, *MAX/MIN Energy-Hop* and (b) *SUM/MIN Energy* and *SUM/MIN Energy-Hop* algorithms. The results were obtained for the case of finite energy and the topology of Figure 1a.

Regarding the number of collisions, the *Minimum-Hop* algorithm almost always results in fewer collisions than the other algorithms (Figure 7). This is not only because it uses a smaller number of packet transmissions for the packets it routes, but also due to the fewer packets it delivers to their destination compared to the other algorithms.



(a) (b)

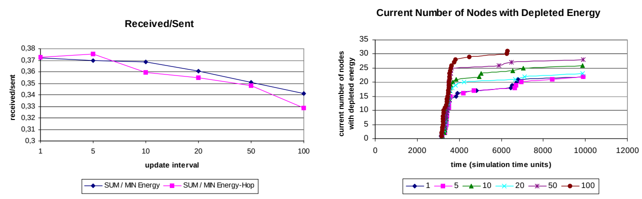
Figure 7. Illustrates the number of collisions for the *Minimum-Hop*, *MAX/MIN Energy* and *MAX/MIN Energy-Hop* algorithms. The results were obtained for the case of (a) infinite and (b) finite energy and the topology of Figure 1a.

6.3 The effect of the duration of the update interval

In this section, we present experimental results obtained for the case of variable update interval. In these experiments the transmission range of each node is 50-100m and each node has to send 1000 packets to a randomly chosen destination. The optimization functions studied are the *SUM/MIN Energy* and the *SUM/MIN Energy-Hop* functions. We did not study the *Minimum-Hop* algorithm, since its routing decisions do not change over time.

When the initial energy of the nodes is taken to be practically infinite, there is no significant difference in the results obtained by both functions, no matter what the update interval is. This is because the changes in the residual energy, which is the only time-varying parameter, are relatively too small compared to the initial value, to trigger significant shifts in the paths used.

When the initial energy is finite, the performance of the energy-aware algorithms degrades as the interval between two successive updates increases (Figure 8). This is because the less frequent updates, make the algorithms become more static and lose their advantages in selecting each time the most energy-efficient paths. Interestingly though, there is a certain threshold in the frequency of the updates under which the performance of the energy-aware routing algorithms is not seriously degraded. In our experiments this seems to be 5 or 10 time seconds.



(a) (b)

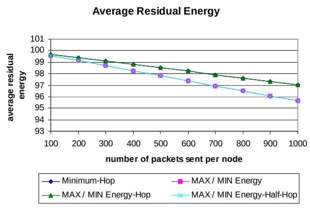
Figure 8. Illustrates (a) the received to sent packets ratio and (b) the current number of nodes with depleted energy for the *Minimum-Hop*, *SUM/MIN Energy* and *SUM/MIN Energy-Hop* algorithms. The results were obtained for the case of finite energy and the topology of Figure 1a.

7 Conclusions

The *Energy-Half-Hop* algorithms were found to behave very similarly to the *Energy* algorithms in all cases considered. This is the reason we chose not to present in great detail the results on the *Energy-Half-Hop* algorithms. It seems that the $\frac{1}{2}$ exponent on the number of hops, effectively eliminates its impact on the cost function (see Figure 9).

In most of the experiments conducted, we found that the behavior of the *Energy-Hop* algorithms was between that of the *Minimum-Hop* algorithm and that of the *Energy* algorithms, and, actually, in most cases it was closer to that of the *Minimum-Hop* algorithm.

Figures 2 and 3, presented earlier, support the above observations.



(a)

Figure 9. Illustrates the average residual energy for the *Minimum-Hop*, *MAX/MIN Energy* and *MAX/MIN Energy-Hop* algorithms. The results were obtained for the case of infinite energy and the topology of the simple 7×7 grid (transmission range fixed at 50 metres).

Another observation concerns the impact of the associative operator (MAX or SUM) used for combining the T_i parameters in the optimization functions. Our results show that the *SUM/MIN Energy* function behaves considerably better than the *MAX/MIN Energy* function. In other words, it seems that summing the values of the transmission powers of the nodes on a path is more representative of the cost of transmitting through this path than taking the maximum value of them. For similar reasons, the *SUM/MIN Energy-Hop* algorithm was also found to behave better than the *MAX/MIN Energy-Hop* algorithm, even though the difference between these two was not as significant as it was between the corresponding *Energy* algorithms. This is because the number of hops factor dominates the cost function in the *SUM/MIN Energy-Hop* and the *MAX/MIN Energy-Hop* algorithms (Figures 4 and 6).

When the transmission range of the nodes was fixed at 50m the number of collisions was far larger (usually around double) than that obtained when the transmission range varied between 50 and 100m. This is because the range at which the Carrier Sensing takes place was taken to be equal to the transmission range. Thus, when this range is fixed at 50m the nodes can sense the medium at a smaller distance, resulting in a larger number of collisions (Figures 7 and 10).

In the experiments where the initial energy of the nodes was taken to be finite (equal to 2 joules), the network performance was found to remain more or less stable after a certain number of packets had been inserted in the network. The reason is that after some point, the nodes that run out of energy limit the ability of the network to transmit packets; offering extra traffic, after this point, does not result in more packets delivered to their destination.

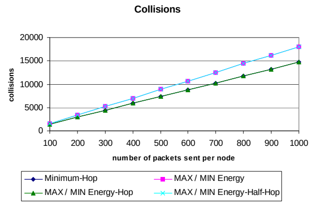


Figure 10. Illustrates the number of collisions for the *Minimum-Hop*, *MAX/MIN Energy* and *MAX/MIN Energy-Hop* algorithms. The results were obtained for the case of infinite energy and the topology of the simple 7×7 grid (transmission range fixed at 50 metres).

Finally, in the experiments we conducted with the transmission range varying between 50-150m, the network is considerably more dense than in the other two scenarios (see Figure 1b). So, there were nodes whose transmission range is so large that they detered many nodes around them from transmitting packets. As a result, in these experiments, the number of successfully transmitted packets was much smaller than in the other two scenarios.

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