A Study of Maximum Lifetime Routing in Sparse Sensor Networks

Ewa Hansen, Mikael Nolin and Mats Björkman
Mälardalen University, Sweden
ewa.hansen@mdh.se

Abstract

A major issue in wireless sensor networks is to prolong network lifetime by efficient energy management. In this paper we present an initial study of maximum lifetime routing in sparse sensor networks. We have studied simulations of how different heuristic routing algorithms influence the energy consumption of individual sensor nodes, and thus the functional lifetime of a sparse sensor network. The functional lifetime of the sensor network can be either until the first node has run out of energy or until a certain threshold of nodes has demised. We have also compared the maximum lifetime of the heuristic algorithms to the maximum lifetime of an optimal routing solution. Our simulations with non-aggregated data indicates that using one of the presented heuristic routing algorithms are not enough to find a near optimal routing. Our study is made in the AROS framework.

1 Introduction

Wireless sensor networks are rapidly becoming common in application areas where information from many sensors is to be collected and acted upon. Using wireless sensor networks adds flexibility to the network, and the cost of cabling can be avoided. One major issue in sensor networks is that wireless nodes most often obtain energy from a local battery. Since this limits the amount of energy available to the node, it affects the lifetime of the node and thus also the functional lifetime of the sensor network. In many application scenarios, replacement or recharging of power resources is costly or even impossible. Energy efficiency thus becomes a major issue in wireless sensor networks.

In this paper we present an initial study of maximum lifetime routing in sparse sensor networks. We have studied simulations of how different heuristic routing algorithms influence the energy consumption of individual sensor nodes, and thus the functional lifetime of a sparse sensor network. The functional lifetime of the sensor network can be either until the first node has run out of energy, or until a certain threshold of nodes have demised, i.e. have no more energy to use.

We have also compared the maximum lifetime of the heuristic algorithms to the maximum lifetime of an optimal routing solution.

The rest of this paper is outlined as follows: in Section 2 we introduce the AROS framework. In Section 3 we describe some related work. Section 4 presents the different heuristic algorithms used in our simulations and in Section 5 the simulation setup is described. The results is presented in Section 6, and finally in Section 7 our conclusions are presented together with some future work.

2 The AROS architecture

The studies presented in this paper are made in the AROS framework [7], and we have therefore focused on sensor networks with infrastructure support.

The AROS architecture [7] is based on cluster groups using base stations with "unlimited" energy and "enough" bandwidth in the backbone network. AROS uses a centralized approach to TDMA-based scheduling where resource-adequate Base Stations have global knowledge of the network and perform all calculations necessary to evaluate routes and schedules, thus relieving sensor nodes from the energy-consuming task of executing complex distributed decision algorithms. The sensor nodes periodically receive updated routing and scheduling information from the Base Station.

AROS divides the time in the network into *rounds*. One round is the time during which all sensor nodes (that wish to send data) send their data to the Base Station. After each round, routes and schedules are recalculated by the Base Station and distributed to the sensor nodes.

The communication between the Base Station and the sensor nodes is asymmetric, i.e. the Base Station can communicate directly with all sensor nodes, but the sensor nodes might have to communicate with the Base Station through other nodes, i.e. multihop.

3 Related Work

A lot of work has been done in the areas of energy efficient routing and power aware routing, e.g. [1, 4, 6, 10, 11] to name a few.

Singh *et* al. [9] presents the PAMAS protocol which is a MAC layer protocol that turns off the radio when the node is not transmitting or cannot receive packets. This protocol saves 40-70% of battery power according to [9]. The paper also includes several power aware metrics that are used to construct energy-efficient routes e.g. *Minimize Energy consumed/packet* and *Maximize Time to Network Partition*.

Li *et* al. [5] presents the *max-min* $z\mathrm{P}_{min}$ algorithm, which combines the benefit of selecting path with both the minimum power consumption and the path that maximizes the minimal residual power in the nodes of the network. An important factor in the *max-min* $z\mathrm{P}_{min}$ algorithm is the parameter z that tries to find a balance between the maximum minimum residual power path and the minimal power consumption path, but it seems that it is not so easy to find the optimal value of z. According to [5], the algorithm requires knowledge about each node in the network which can be a problem when implementing the algorithm in large networks. To solve this problem they propose a zone-based routing that relies on *max-min* $z\mathrm{P}_{min}$ but is scalable. In zone-based routing the network is divided into smaller zones, and each zone has only control over how to route the messages within its own zone. A global path across zones is also computed.

Chang *et* al. [1] presents a flow augmentation algorithm (FA) which is a shortest cost path routing where the link cost is a combination of transmission and reception energy consumption and the residual energy level at the two end nodes. The objective in [1] is to find the best link cost function which leads to the maximization of the system lifetime. When there is plenty of residual energy in the nodes, the energy cost term is emphasized, but when the node has less residual energy, the residual energy term has greater impact,i.e. is given more weight in the cost function.

Shah *et* al. proposes in [8] a scheme called energy aware routing that uses sub-optimal communication paths occasionally. The basic idea behind the scheme is to increase the survivability of the network by sometimes communicating through a sub-optimal path. They use a set of good paths and choose one of them, based on some probabilistic function. This means that instead of using one single communication path, different communication paths will be chosen at different times, thus any single communication path will not suffer from energy exhaustion.

4 Heuristic algorithms

As mentioned above, we want to maximize the functional lifetime of our network. Depending on the application and the amount of redundancy in the network, the functional lifetime can range from the time when the first node demises (in the case of no redundancy) to the time when all nodes have demised (in the case of full redundancy).

Our envisioned applications (industrial, hospital, domestic) are not likely to provide full redundancy. That means, the lifetime of individual nodes become more important. For a network with no redundancy, the optimal algorithm should keep all nodes alive as long as possible, i.e. until all nodes run out of energy at the same time. For a network with some degree of redundancy, some nodes can be allowed to run out of energy early, if that prolongs the lifetime of the rest of the nodes.

An optimal routing strategy should be able to construct a new routing scheme for every round in the network. Since our envisioned applications are not fully static (albeit slow to change), the new routing schemes must be constructed within limited time frames. Hence, it is not possible to make an exhaustive off-line scheduling of the network for its entire lifetime. Rather, the time available to construct the new schedule is likely to be in the order of a few seconds (or maybe even less). This implies that we must use efficient heuristics in order to meet the timing demands of the applications.

In our first approach to find such heuristics, we have investigated the relative efficiency of a number of heuristic algorithms. We want to find out if there is one single heuristic that suits our type of networks best. Should this not be the case, we want, in future studies, find under what circumstances the different algorithms are most efficient. If we can find good heuristics for when to change algorithm, we could in this case be more efficient than always using one single algorithm.

4.1 The algorithms studied

In order to find the most power efficient routes in our network, we have studied a number of simple heuristic algorithms that can be used to approximate the optimal routes. In this section we describe the algorithms we have studied.

During one *round*, all nodes send their sensed information/data *once* to the Base Station. The information is either sent directly to the Base Station, or through other nodes. When information from all nodes has been sent to the Base Station, a new routing scheme is made and a new round begins.

4.1.1 Minimum total energy consumption, MTEC

In the first algorithm, MTEC, we want to minimize the total energy consumption for the whole network, as in equation 1. In equation 1, e_i is the energy consumption for node i when sending to the Base Station and n is the number of nodes.

$$Min \sum_{i=1}^{n} e_i \tag{1}$$

The rationale behind this algorithm is that a smaller total energy consumption in the current round means that more energy will be left to coming rounds, i.e. the network as a whole will live longer. The balance between the energy consumption of individual nodes is however not considered in this algorithm.

4.1.2 Minimum squared energy consumption, MSEC

The second algorithm, MSEC, is based on the consideration that one node can be very heavily loaded, but the total energy consumption can still be the lowest. In this algorithm, we square the energy consumption of each individual node before we sum the energy consumption, as in equation 2.

$$Min\sum_{i=1}^{n}(e_i)^2 \tag{2}$$

The rationale behind this algorithm is that routes where one node is heavily loaded will get a higher sum and thus be less likely to be chosen as the best route. Hence, we will get more equally loaded nodes than in the first algorithm, equation 1, while still choosing a route with a low total energy consumption.

4.1.3 Minimal maximum individual energy consumption, MMIEC

In our third algorithm, MMIEC, we minimize the maximum energy consumption for a single node. This is shown in equation 3, where e_{max} is the maximum energy consumption for a single node in the chosen route.

$$Min(e_{max}) \tag{3}$$

The rationale behind this algorithm is that if we can minimize the maximum energy consumed by one node, we can prolong the lifetime for the node that consumes the most energy for a given route, and thereby prolong the lifetime of the whole network. One drawback can be that if all nodes consume almost the same amount of energy the network may demise quickly.

4.1.4 Minimal difference in energy consumption, MDEC

Our fourth algorithm, MDEC, makes the difference in energy consumption between the most consuming and the least consuming node as small as possible. This is shown in equation 4, where e_{max} is the maximum energy consumption for a single node and e_{min} is the minimum energy consumption for another single node.

$$Min(e_{max} - e_{min}) \tag{4}$$

The rationale behind this algorithm is that this algorithm makes the average energy consumption approximately equal between the nodes. This approach can however be less efficient if all nodes consume a lot of energy. In this case the difference between the nodes' energy consumption can be small but the energy consumption for each individual node might be high. This would lead to shorter lifetime for the network.

4.1.5 Maximum squared remaining energy, MSRE

In the fifth algorithm, MSRE, we have studied the remaining energy of the nodes, taking the maximal sum of the squares of the remaining energy. This is shown in equation 5, where e_{left} is the remaining energy for a single node.

$$Max\sum_{i=1}^{n}(e_i^{left})^2 \tag{5}$$

This algorithm tries to maximize the remaining energy of the system. Since the square of the remaining energies are used in the sum, the algorithm will favor routes where one (or more) nodes have much energy left. For networks where the functional lifetime of the network continues until all nodes have demised, this can be beneficial. However, since the algorithm favors energy unbalance in the network, the first node (or nodes) is likely to demise earlier than when using algorithms that favor energy balance.

4.1.6 Maximal minimum individual remaining energy, MMIRE

The sixth algorithm, MMIRE, maximizes the minimum energy left for a single node. This is shown in equation 6.

The energy left after a chosen round is calculated in advance and the most exposed node, i.e. it has the lowest energy left, is maximized, this to not expose one single node more than needed.

$$Max(e_{min}^{left}) \tag{6}$$

The rationale behind this algorithm is that it makes the most exposed node during one round hopefully less loaded during the next rounds, thus spreading the energy consumption more evenly over the nodes. One drawback with this approach is that only one node is under consideration.

5 Simulation setup

For the simulations presented in this paper we have implemented a routing system and a simulator.

We have made simulations with 100 randomly generated sensor networks. The network area was 400x400 m^2 and the number of nodes randomly spread across the network was 5. These nodes can be considered as either ordinary sensor nodes or cluster head nodes in a cluster-based sensor network, e.g. as in the AROS project [7]. The reason for using a small amount of nodes is that we want to be able to compare results from our heuristic routing algorithms to results using an optimal routing solution. To simulate the optimal routing is too resource-consuming to be feasible to calculate for larger numbers of nodes. To be able to find the optimal route, we have made a complete search among all possible routes, and the most energy efficient[1] result is found.

When calculating the energy consumption of the sensor node radio transmitter, we have used the same equation as in

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[1] Most number of rounds.

Table 1. Non-Aggregated data

	MTEC		MMIEC		MDEC	
	$\bar{a}$	σ	$\bar{a}$	σ	$\bar{a}$	σ
5 nodes	13,11	13,17	15,93	14,18	14,83	12,86
4 nodes	7,59	8,76	5,3	11,18	4,54	10,33
3 nodes	6,88	11,25	6,39	12,04	6,10	13,51
2 nodes	13,69	29,11	11,26	30,77	11,26	33,88
Total	**41,27**	**16,36**	**39,38**	**17,70**	**36,73**	**18,57**

	MSRE		MMIRE		MSEC	
	$\bar{a}$	σ	$\bar{a}$	σ	$\bar{a}$	σ
5 nodes	12,27	12,38	2,07	1,60	15,27	13,95
4 nodes	7,49	8,72	3,28	3,68	6,16	10,96
3 nodes	7,09	11,70	5,59	6,30	6,56	11,94
2 nodes	14,79	30,92	21,35	32,59	12,62	32,86
Total	**41,64**	**16,97**	**32,29**	**16,75**	**40,61**	**18,27**

[2, 3, 7]. When sending a message a distance up to 87 meters, we have used $\epsilon_{friss-amp} = 10pJ/bit/m^2$, and when sending a distance of more than 87 meters we have used $\epsilon_{two-ray-amp} = 0.0013pJ/bit/m^4$. The radio electronics consume $E_{elec} = 50nJ/bit$. The equation for calculating the total amount of energy consumed when sending a message of b bits a distance of d meters is then:

$$E_{Tx} = \begin{cases} b * E_{elec} + b * \epsilon_{friss-amp} * d^2 & : d < 87m \\ b * E_{elec} + b * \epsilon_{two-ray-amp} * d^4 & : d \geq 87m \end{cases} \tag{7}$$

The amount of energy used by a sensor node radio receiver when receiving a message is:

$$E_{Rx} = b * E_{elec} \tag{8}$$

In our simulations, each node starts with an energy of 0,1 mJ[2]. All nodes consume energy when transmitting and receiving data packets. When not transmitting or receiving, the nodes are in sleep mode and are assumed to use very little energy. In this paper this energy is assumed negligible.

We have performed simulations with both aggregation and non-aggregation of data, where aggregation means that a downstream node can aggregate two (or more) messages of size N, bound for the same destination, into one single message of size N. This enables us to study if there are differences between aggregation and non-aggregation with respect to what algorithms perform best in our scenarios.

6 Results

In this section, we present some results from our studies. We have made an initial study of maximum lifetime routing in sparse sensor networks. We have studied simulations of how different heuristic routing algorithms influence the energy consumption in individual sensor nodes, and thus the functional lifetime of a sparse sensor network. We have also compared the maximum lifetime of the heuristic algorithms to the maximum lifetime of an optimal routing solution.

The results are from simulations with non-aggregated data and from simulations with aggregated data. We have calculated the energy consumption E_{Tx}, using equation 7, when sending and E_{Rx}, using equation 8, when receiving. All nodes that receives data consumes E_{Rx} for each message it receives. When aggregating data a node uses E_{Tx} for the one (aggregated) message it sends, and when not aggregating data it uses E_{Tx} for each message it forwards.

We have also compared the results from the different algorithms with an optimal routing solution. The optimal routing solution in this paper is simulated the same way as the other algorithms, but instead of running one of the heuristic algorithms, a complete search tree is computed and the most energy efficient [3] result is found.

6.1 Results of heuristic algorithms

In tables 1 and 2, we can see results from the six algorithms described in section 4. The average number of rounds ($\bar{a}$) and the standard deviation (σ) are calculated for all the algorithms. We also show all the separate numbers of rounds, from when the first node runs out of energy until it is only one node left in the network. i.e. 5 nodes = number of rounds with all nodes alive, 4 nodes = number of rounds with one node demised, and so on. *Total* is the total number of rounds until all nodes have run out of energy. We have, in this paper, concentrated on two different functional lifetimes, as mentioned in Section 4. The two functional lifetimes are; until the first node demises and until all nodes have demised.

6.1.1 Non-aggregated data

When looking at the results from our simulations with non-aggregated data, found in table 1, we can see that the average number of rounds until the networks have demised differs a bit among the algorithms, although in most cases not much. When choosing route using MSRE (equ. (5)), we can see that this results in the most energy-efficient routing, but using MTEC (equ. (1)) is almost as good. When choosing MMIRE, (equ. (6)) we can see that this approach is not quite as good as the other approaches. MMIRE is not good at all if we want to maximize network life time until the first node demises. We can see that the other algorithms run approximately 6 to 8 times more rounds before the first node demises.

Another point worth noting is that MDEC has the shortest total network lifetime, if not including MMIRE. This is not surprising, since, as noted in Section 4, MDEC will even out energy differences, but does not consider the total energy consumption. An indication of this property is also that the lifetime until the first node demises is relatively good for MDEC, since MDEC tries to balance energy consumption as much as possible, thus keeping all nodes alive

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[2] The reason for the small amount of initial energy is due to the execution time of the simulation.

[3] Most number of rounds.

Table 2. Aggregated data

	MTEC		MMIEC		MDEC	
	$\bar{a}$	σ	$\bar{a}$	σ	$\bar{a}$	σ
5 nodes	37,75	35,00	37,8	35,02	37,67	35,04
4 nodes	20,96	28,54	20,9	28,65	19,79	29,26
3 nodes	19,79	38,60	19,56	38,66	15,98	33,03
2 nodes	29,77	68,89	29,54	68,92	28,4	71,91
Total	**108,27**	**42,45**	**107,8**	**42,48**	**101,84**	**42,61**
	MSRE		MMIRE		MSEC	
	$\bar{a}$	σ	$\bar{a}$	σ	$\bar{a}$	σ
5 nodes	37,41	34,56	3,73	3,39	37,79	35,02
4 nodes	21,01	29,08	4,66	4,82	20,99	28,54
3 nodes	19,72	38,57	8,55	10,67	19,82	38,64
2 nodes	29,57	69,21	26,48	44,57	29,68	68,88
Total	**107,71**	**42,51**	**43,42**	**22,59**	**108,28**	**42,45**

for a relatively long period.

MSRE is quite the opposite to MDEC. MSRE has bad results for the number of rounds until the first node demises, but has the longest total lifetime of all algorithms. This is consistent with the discussion in Section 4, MSRE favors one (of a few) nodes with much energy left, and this is likely to lead to the early demise of one of the other nodes.

6.1.2 Aggregated data

When looking at the results from our simulations with aggregation of data, found in table 2, the differences among the algorithms are not big, although there are some differences. In these simulations one of the algorithms is again different from the others, MMIRE (equ. (6)). When aggregating data, the other algorithms runs approximately 10 times more rounds, compared to MMIRE, before the first node demises.

The conclusions from these comparisons are that several of the heuristic algorithms exhibit a similar behavior, when looking at the mean values and standard deviations of the same 100 generated networks. Also, it is clear that the MMIRE algorithm is not as good as the other heuristic algorithms.

6.2 The algorithms compared to optimal results

When simulating the optimal routing solution, we selected one of the most energy-consuming networks among the 100 randomly generated networks, and compared the result with our heuristic algorithm results. The reason for choosing one of the most energy-consuming networks was due to the execution time of the optimal solution. The cost of finding the optimal solution is exponential to the number of rounds, so only networks with small numbers of rounds are feasible to find the optimal solution for.

6.2.1 Non-aggregated data

When comparing the non-aggregated results from the heuristic algorithms with the optimal solution for non-aggregated data, the differences are more significant when comparing the number of rounds until all nodes have demised. None of the heuristic algorithms could match the optimal solution of a total of 9 rounds. The two heuristic algorithms that managed best were MTEC and MSRE with 7 rounds. MMIEC and MMIRE managed 6 rounds and MDEC and MSEC only managed 5 rounds before all nodes had demised.

Comparing the number of rounds until one node had demised resulted in 3 rounds for the optimal solution, MMIEC, MDEC, and MSEC. MTEC managed 2 rounds and MSRE and MMIRE only 1 round. Again MMIRE, as mentioned above, is not as good as the other algorithms.

The conclusions from this comparison are first of all that for non-aggregated data, the heuristic algorithms were far from optimal even for a network that only survived 9 rounds. Also, there are clear differences between the heuristic algorithms when examining one single network. Finally, it is clear that the MMIRE algorithm is not a good algorithm.

6.2.2 Aggregated data

When comparing the aggregated data simulations to the optimal routing solution for aggregated data, the differences are very small or none. (We only compared the total number of rounds, and the number of rounds until one node had demised.) The total number of rounds for the optimal solution and for four of the heuristic algorithms was 13 rounds. The algorithms that were different were MDEC and MMIRE, which had fewer rounds, 10 and 6 respectively.

When comparing the heuristic algorithms to the optimal solution until one node had demised, there was only one algorithm, MMIRE, that showed fewer rounds, 2, than the optimal solution. All the other algorithms showed the same number of rounds, 4, as the optimal solution. (As mentioned earlier, the MMIRE algorithm is not as good as the other algorithms.)

7 Conclusions and Future Work

In this paper we have made an initial study of maximum lifetime routing in sparse sensor networks. We have studied simulations of how different heuristic routing algorithms influence the energy consumption in individual sensor nodes, and thus the functional lifetime of a sparse sensor network. We have also compared the maximum lifetime of the heuristic algorithms to the maximum lifetime of an optimal routing solution.

When looking at the simulation results with aggregated data we can see that it is not a big difference among the heuristic algorithms. The algorithms MSEC and MTEC are the two heuristic algorithms that show the best results. The heuristic algorithm that shows the worst results is clearly MMIRE, see table 2.

When comparing these heuristic algorithms to the optimal routing solution (one of the most energy consuming network setups), the differences are very small or none. The total number of rounds for the optimal solution and for four of the heuristic algorithms was 13 rounds. The algorithms that were different were MDEC and MMIRE, which had fewer rounds, 10 and 6 respectively.

When looking at the simulation results with non-aggregated data, the differences among the heuristic algorithms were slightly bigger. If only looking at the total number of rounds until all nodes have demised, MSRE, MTEC, MSEC and MMIEC were the four heuristic algorithms that performed best (when comparing both the average number of rounds and the standard deviation). When comparing the number of rounds until one node had demised, MSEC and MDEC were slightly better than the others. Looking at MMIRE, we can see that this heuristic algorithm is not good at all if we want to maximize network life time until the first node demises.

Comparing to the optimal routing solution, the differences are more significant when comparing the total number of rounds. None of the heuristic algorithms could match the number of rounds for the optimal solution. The two heuristic algorithms that managed best were MTEC and MSRE.

The conclusions of these simulations are that when aggregating data, the choice of heuristic algorithm is not as significant as when not aggregating data. Some differences have been identified and one of them is that MMIRE is not a good heuristic algorithm.

Our simulations with non-aggregated data indicates that using one of the presented heuristic routing algorithms are not enough to find a near optimal routing, hence it is possible that several different heuristic algorithms need to be combined to find a near optimal routing solution.

In the future we will continue our work to prolong network lifetime e.g. until the first node demises (in sparse networks) or until some threshold of nodes have demised (in more densely populated networks). The initial studies in this paper is the beginning of ongoing work where we plan to investigate how we can combine these heuristic algorithms to be able to find a near optimal routing solution. We will investigate when to change heuristic and what heuristic that is most suitable in different situations. We will also investigate for what kinds of network setups different heuristic algorithms are most suitable, e.g. for what kind of network setup is MMIES most suitable? In future work we will also try to find a near optimal routing solution by e.g. weighting each link so that no node drains its energy faster than the other nodes, i.e. avoiding hotspots.

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