Efficient Routing for the Extension of Lifetime and Quality of Energy Constrained Ad Hoc Networks

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Abstract. This paper presents two new routing algorithms for maximising the lifetimes of wireless energy-constrained ad-hoc networks. Our approach is based on the homogenisation of energy consumption in the network as opposed to the more traditional approach where the paths are chosen based upon highest energy. Results show the relative merits of the proposed schemes with respect to existing energy-aware protocols and clearly indicated that the two proposed algorithms enable full network connectivity to be maintained for longer. Additionally, the two algorithms mitigate against the effects of inevitable node outages caused by energy exhaustion and offer an improved likelihood of maintaining connectivity when nodes are lost by comparison with other previously proposed algorithms.

Keywords: Ad hoc routing, energy-aware routing, grid topology, energy homogeneity.

1 Introduction

Progressive technology advances have made it possible to build ad-hoc, low power, wireless sensor networks \cite{1} of hundreds and even thousands of devices of low computation, communication and battery power. Potential uses of such devices are manifold. For example, such networks can be used to monitor large geographical areas in remote surroundings, factory and plants or chemical processes, home automation, and personalisation applications.

Typically, devices are battery powered and since every message transmitted and received and the associated computation performed drains the battery, care is required in the utilisation of power.

Power efficient routing algorithms are very important in wireless sensor networks, where communication costs are more expensive than computing costs \cite{2}. Different power-aware routing protocols \cite{3} define the cost as a function of the power required to transmit over links and
then employ minimum cost routing algorithms to find the minimal energy route from sources to destinations.

However, the lowest-power path, from the network lifetime perspective, may not be the optimal route. To avoid the node extinction resulting from battery power depletion, energy aware routing algorithms try to ensure an equitable distribution of the transmission cost among all nodes. In this paper, we propose two new algorithms for energy aware routing in large networks and compare their performance with a range of standard algorithms: Strongest Path Routing (SPR) and Min-Max Battery Cost Routing (MMBCR), see, e.g., [4]. Being intrinsically simple in terms of route calculation, our algorithms compare favourably to the latter more complex routing schemes in terms of the attained lifetime. Moreover, they outperform the existing algorithms in the quality of the remaining energy field by maintaining overall homogeneity in the nodes energies.

In practical applications, the lifetime of a network is a function comprising many factors, [5], [6], [7], [8]: the routing protocol used is only one of these. To single out the influence of this main factor and to provide a fair comparison of different routing disciplines, we purposely ignore many specifics of the real ad-hoc networks, and consider the simplest network topology where the devices are arranged in a two dimensional square grid.

2 Model Description

Consider a planar network $G$ composed of $M = N^2$ nodes with coordinates $(X_i, Y_i) \in \{1, 2 \ldots, n\} \times \{1, 2 \ldots, n\}$. The energy level of a node $N_i \in G$ at time $t$ is an entire number $E(N_i(t)) \geq 0$, the node is ‘alive’ at time $t$ if $E(N_i(t)) > 0$ and ‘dead’, otherwise. The energies are not restorable, so once a node ‘dies’ it stays inactive forever. Each node has radio interfaces, capable of communicating with all the neighbouring nodes which are all the nodes withing the distance 1. At every discrete point of time $t, t = 1, 2, \ldots$, a node $S = S(t) = (X_s, Y_s)$ (source) sends a packet to a destination node $D = D(t) = (X_d, Y_d)$ which is instantly relayed through a sequence

$$J(t) = [S(t) = N_{i_0}(t) \rightarrow N_{i_1}(t) \rightarrow \ldots \rightarrow D(t) = N_{i_l}(t)]$$

of neighbouring nodes alive at time $t$. The energies of all the nodes on the path are then reduced by 1 unit.

The path taken by the packet is determined by the routing protocol used among the set $R(S(t), D(t))$ of feasible paths. We assume that the feasible paths are those that contain only active nodes which only move packets in the direction of the destination. In our grid, this means that loop-free feasible paths all lie inside the rectangle formed by $S$ and $D$ in the corners. The number of nodes in the path is then equals its Euclidean length $l = |X_s - X_d| + |Y_s - Y_d|$. If all the nodes in the rectangle are active, the total number of possible paths from $S$ to $D$ then equals the Binomial coefficient $\binom{4t}{|X_s - X_d|}$.

We implicitly assume that the routing algorithms require complete knowledge of the location and energy levels of the nodes in the network at all times. However, no knowledge of future transmissions is assumed. In practical sensor networks, the full knowledge of the energy distribution for all nodes and by all nodes is generally not achievable. However, knowing an optimal strategy for the whole system permits distributed variants of the protocol to be applied to configuration sets known to the sending nodes.
We next describe two new algorithms to extend lifetime and quality of networks: the Point to Diagonal Algorithm (PTD) and the Point to Zero Algorithm (PTZ).

The state of the network at any time $t$ can be described by a $E(t)$ of the space $\mathbb{R}^M$, whose coordinates represent the remaining energies of the nodes at time $t$: 

$$E(t) = (E_1(t), E_2(t), \ldots, E_M(t)),$$

where $E_i(t) = E(N_i(t))$, $i = 1, \ldots, M$. Transmitting a packet over a path $J(t)$ as in (1), will result in decreasing by one the energies of the corresponding transmitting nodes. If $\pi(t)$ is the $M$-dimensional vector having 1 at the coordinates $i_k$ such that $N_{i_k}(t) \in J(t)$, $k = 0, \ldots, l$ and 0 in all other coordinates, then the resulting energies at time $t+1$ will be $E(t + 1) = E(t) - \pi(t)$. Therefore, evolution of the system is completely described by the initial energy distribution and either a sequence of vectors $\pi(t)$ or a sequence of the remaining energies $E(t)$ for all $t$.

3 Proposed Energy Homogenising Algorithms

When the energy of a node drops to 0, the vector of remaining energies lies on a lower dimensional subspace of the quadrant $\mathbb{R}^M$ thus significantly reducing the choice of paths for subsequent transmissions. A good routing protocol should prevent this from happening for as long as possible in order to extend network lifetime.

The PTD algorithm aims to keep the energy vector $E(t)$ at every moment $t$ as close as possible to the diagonal line $\Delta = (C, C, \ldots, C)$ of $\mathbb{R}^M$ thus maintaining the homogeneity of battery reserve distribution in the network. The PTZ algorithm tries to maintain the same relative proportion of the remaining energies between the nodes, anticipating the situation when the overall re-balancing of the energies maybe impractical.

3.1 Point to Diagonal Algorithm (PTD)
The PTD algorithm attempts to maintain even energy consumption throughout the network. This will avoid the unwise overuse of nodes.

Every time node $N_i$ transmits a message, its battery reserve decreases, therefore the overused nodes quickly lose their energy. Geometrically, this means that the energy vectors $E(t)$ approach the hyper-plane $E_i = 0$. We endeavour to avoid this situation and prefer networks containing nodes with homogeneous energy levels rather than networks whose nodes exhibit large fluctuations in energy levels. This translates into forcing the multidimensional point $E(t)$ to be as close as possible to the diagonal $\Delta$. Remember, the diagonal is the set of points farthest away from the multidimensional spaces defined by network status containing dead nodes. Consequently we propose an algorithm that, at time $t$ selects the routing path $\pi(t)$, minimises the distance from $E(t+1)$ to the projection point of $E(t)$ onto $\Delta$.

The algorithm works in the following way. Given a communication request from the source node $S(t)$ to destination $D(t)$ at time $t$, let $R(t) = R(S(t), D(t))$ denote the set of vectors $\pi$ corresponding to all feasible paths from $S(t)$ to $D(t)$. The set $E(t) - R(t)$ thus represents the range for $E(t+1)$. Elementary geometrical calculations show that the projection of a vector $(E_1(t), \ldots, E_M(t))$ onto $\Delta$ is the point at which $E(t) = M^{-1} \sum_{i=1}^{M} E_i(t) - \text{the mean energy of a node}$. The PTD algorithm then chooses the path corresponding to $\pi(t)$ which minimises

$$\sum_{i=1}^{M} (E_i(t) - \pi_i(t) - \overline{E(t)})^2.$$  \hspace{1cm}(2)

So, effectively, PTD minimises the variance of the energy distribution in the network.

For instance, on Figure 1 the set of possible values for $E(t+1)$ are three points: $E_1(t+1), E_2(t+1)$ and $E_3(t+1)$. The PTD algorithm will then choose the path corresponding to $E(t) - E_3(t+1)$.

If there are multiple energy vectors in $E(t) - R(t)$ realising the minimal distance to $\Delta$, then the path is randomly chosen among these optimal routes.

3.2 Point to Zero Routing Algorithm (PTZ)

![Fig. 2. Path selection for PTZ.](image)

The idea behind the PTZ algorithm, as with PTD, is to proportionally decrease the energy states of the network while avoiding converging too quickly towards states containing one or
more zero energy components. This is done in a less constrained way than PTD. In every energy state $E(t)$, the algorithm tries to select a path leading to the new state $E(t+1)$ minimising the distance to $(OE(t))$ among all feasible energy states $E(t) - R(t)$, $(OE^n)$ being the line passing through the origin $O$ and $E(t)$, see 2).

It is easy to obtain the projection of a vector $E(t+1) = E(t) - \pi(t)$ onto the line $(0, E(t))$ is the point $\alpha E(t)$, where

$$\alpha = 1 - \frac{E(t) \cdot \pi(t)}{\|E(t)\|^2} = 1 - \|E(t)\|^2 \sum_{i_k \in J(t)} E_{i_k},$$

where $a \cdot b$ is the scalar product of vectors $a$ and $b$ and $\|E\|^2 = \sum_{i=1}^{M} E_i^2$. Thus, the PTZ algorithm chooses a feasible $\pi(t)$ minimising

$$\sum_{i=1}^{M} \left[ \frac{E(t) \cdot \pi(t)}{\|E(t)\|^2} E_i(t) - \pi_i(t) \right]^2.$$

If there are multiple $\pi(t)$ providing such a minimum, the priority is given to the one for which $E(t) - \pi(t)$ is closest to the diagonal $\Delta$. If there are multiple points the same distance from the diagonal, a point is chosen from this set at random.

### 4 Reference Routing Algorithms

In order to assess the quality of the proposed algorithms they are compared with two reference algorithms: Strongest Path Routing (SPR) and Min-Max Battery Cost (MMCBC) routing algorithm. Both algorithms associate a certain cost with each feasible route and chose the one which has the smallest cost. If there are multiple minimal cost routes, then one is chosen randomly.

#### 4.1 Min-Max Battery Cost Routing Algorithm (MMBCR)

MMBCR algorithm chooses the route that has the highest value for the battery reserves of its weakest node among all the feasible routes. This type of routing is considered as standard in many implementations of sensor networks (see [4]).

#### 4.2 Strongest Path Routing (SPR)

Another type of routing is choosing the path with the largest sum of energies of the participating nodes. Since the number of feasible paths maybe significant, the maximal energy path is detected by running a simple path search algorithm. As the algorithms are not anticipating the future, choosing the maximal energy path every time is, perhaps, the most natural strategy. On the other hand, running SPR every time is computationally consuming and may not be practical. However, it represents a suitable benchmark in terms of performance comparison. SPR is similar though not equivalent to Minimum Battery Cost Routing (MBCR) routing, see, e.g., [4].
5 Results

The results presented in this paper were obtained using a C++ simulator and plotted and analysed using R statistical package (see [9]). In all the experiments, the network is a 10 × 10 grid with \( M = 100 \) nodes. Two configurations of initial node energies are considered: either all set to 20 (denoted by IC20 in the sequel) or independently uniformly distributed in the range from 10 to 20 (notation: IC10-20). Randomly charged nodes represents a situation that exists after a certain time of functioning of the system (to study relaxation phenomena of different algorithms) or when the nodes were in different external environment for some time prior to the start of the service or when ‘falling asleep–awakening’ protocols were used. The use of randomly assigned initial energies also enables us to better distinguish between PTD and PTZ algorithms as the starting line \((0, E(0))\) in PTZ coincides with \(\Delta\) in the case when the initial energies are equal.

Two hundred different sufficiently long sequences of the communication requests \((S(t), D(t)), t = 0, 1, \ldots\) was generated to test all four considered routing algorithms: PTD, PTZ, SPR and MMBCR. Moreover, since the algorithms sometimes choose paths randomly, 50 runs were carried out for each of these sequences of requests. In making the comparisons between algorithms a range of derived statistics are used. One area of interest is the point at which full connectivity is lost; this can either described by the point at which the first node (out of the grid) becomes permanently inactive as result of energy reserves being fully depleted OR the point at which the first call request is rejected because no suitable path can be found. There is a significant difference between these two events. The former is the point when 100% connectivity can no longer be guaranteed and thus there is the potential for calls to be rejected. The latter is the first point at which this potential is realised. Also recorded are the points at which further nodes \((10, 20, 30, \ldots)\) become permanently inactive, along with the associated running total of supported and rejected call requests.

The first observation we make is the relatively large variability in the node lifetime as a function of the particular simulated sequence of the communicating pairs \((S(t), D(t)), t = 0, 1, \ldots\). On the other hand, any variation in the lifetime that results from random choice of equivalent paths is usually just a few units. Figure 3 shows lifetimes achieved by running PTZ algorithms on 200 sequences with the initial nodal energies of 20. For a given sequence number, the dot shows the lifetime averaged over 50 realisations of the same sequence of transmissions together with the segment representing 95% confidence interval for the lifetime estimated from these 50 iterations. Variations here are due only to a randomised choice of an optimal path if there are multiple equivalent paths. The horizontal lines represent the overall mean lifetime (194.5 here) and overall 95% confidence bounds.

A similar picture is observed for all other algorithms: for IC20 the overall mean lifetimes are 194.4 for PTD, 192.5 for SPR and 168.6 for MMBCR, therefore the comparison of algorithms is impossible solely on the basis of the overall mean lifetimes achieved. A correct comparison of two algorithms is to consider the sample lifetimes as paired observations as they share the same sequences of communicating pairs. As the distribution of lifetimes is far from being Normal, a non-parametric Wilcoxon signed rank test was employed to test if the lifetimes have the same or different means.
Fig. 3. Average lifetime for 200 realisations of communicating pairs sequences (algorithm PTZ with initial energies 20 for all nodes).

5.1 Lifetime Analysis

The simulation results show that the two algorithms: PTD and PTZ give the same lifetime: any difference of the corresponding means for given sequence of communicating pairs is not significant. For instance, in case of IC20, PTD performed significantly (with 95% confidence level) better than PTZ for seven sequences (solid dots on Figure 4(a)) and for 8 sequences PTZ outperformed PTD (crossed dots). In another 191 cases, the Wilcoxon test shows no significant difference in means (empty dots). Observe a few zero points. With the initial energy point $E(0)$ lying on the diagonal $\Delta$, PTD and PTZ actually coincide.

A similar picture emerges for IC10-20: in 12 cases PTD was better and in 15 cases PTZ appeared to be better. In the remaining 173 cases there were no significant difference, see Figure 4(b)).

Next best algorithm is STR. Although the overall average (192.49 for IC20 and 122.1 for IC10-20) are very close to PTD, for IC20, in 97 communicating pairs sequences PTD outperformed STR compared to only 2 sequences when STR was better. For IC10-20 the figures are 105 and 4, respectively. It is easily seen in Figures 4(c)) and 4(d) that, in many cases, PTD carried more than 10 (and sometimes more than 20) additional requests than STR until the transmission failure due to the absence of any available path.

The worst in terms of achieved lifetime is MMBCR routing. Showing the average number of successful transmission of 168.6 for IC20 and 106.6 for IC10-20, in all cases for IC20 and in 184 cases for IC10-20, PTD/PTZ performed significantly better.

Comparisons between the remaining algorithm pairs lead to the following lifetime performance ordering relationship: PTD = PTZ > STR >> MMBCR. Not only do the proposed new algorithms perform better, they also attain better quality of residual energy configurations, considered in the next section.
Fig. 4. Number of successful connections vs. communicating pairs sequence number
5.2 Request and Node Loss

The results discussed in the previous section clearly indicate that the two proposed algorithms (PTZ and PTD) offer potentially improved performance when compared to the two benchmark algorithms (SPR and MMBCR) with respect to the point when full connectivity can no longer be guaranteed. Further experiments were undertaken to determine the relative merits of each algorithm as the network energy levels were allow to further decay and nodes progressively became inactive. Results were obtained for both homogeneous and random initial energy levels when the networks were allowed to degrade to 90%, 80%, 70%, 60% and 50% of initial capacity interms of active nodes. Figures 5 show the mean call request rejection ratio as a function of the number of remaining active nodes for both initial energy distributions. As it can be seen, both PTZ and PTD algorithms outperform the SPR algorithm in terms of their ability to support requests in situations when full network connectivity cannot be guaranteed. The request rejection ratios for PTD and PTZ are indistinguishable and both are lower than that obtained for SPR for the same number of active nodes. Indeed, it appears that the use of PTD/PTZ algorithms gives a rejection performance benefit equivalent to having (at least) 3 extra active nodes. MMBCR is also offers inferior performance as compared to the proposed algorithms.

This maybe explained by the fact that PTD and PTZ attain more homogeneous energy configuration. Figure 6 shows a typical distribution of the energy at nodes at the time (specific for each algorithm) the first node dies. It is seen that MMBCR under-utilises the boundary nodes while overloading the central ones, while STR produces more spiky configuration than the smoother PTZ and PTD. The two new proposed algorithms seem to more evenly use the network resources.
Fig. 6. A typical energy configuration when the first node dies.
6 Future Work

For the two new routing algorithms suggested in this paper, global knowledge is required and this is not feasible for real life applications. In order to maintain global knowledge of the system, background-overhead traffic must be carried by the energy constrained network. However, there is the danger that, more energy will be expended for collecting this global knowledge compared to the merit gained, and this will result in a reduction of the network lifetime. Hence, modified versions of the routing algorithms will be necessary which will operate in a distributed manner or use partial knowledge of the network state.

Therefore it is necessary to simulate and test further more scenarios, including non-regular topologies and scenarios that try to balance any tradeoff between accuracy of the global knowledge versus homogeneity.

7 Conclusions.

We have proposed two new algorithms that show potential in extending the lifetime of a sensor network. The premise behind these algorithms is that homogenisation of the energy distribution is a key factor in providing loss free operation for as long as possible. The two proposed algorithms have been shown, through simple models, to offer the ability to extend the lifetime of a sensor networks where energy dissipation is critical when compared to other previously proposed algorithms. Furthermore, we have also shown that the two algorithms continue to offer superior performance as the network state (energy distribution) degrades in relation to a significantly better call-rejection ratios. The algorithms tend towards forcing a more homogeneous energy distribution, regardless of the initial state of the network. The use of the PTD/PTZ algorithms ensures that the loss of nodes as a result of energy exhaustion will not be as catastrophic as connectivity (between node pairs) is more likely to be preserved and will give operators more time to take remedial action in the form of sensor replacement or battery recharge and with reduced disruption.

References

