Load-Balancing Strategies for Lifetime Maximizing in Wireless Sensor Networks

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***Abstract*—The lifetime of Wireless Sensor Networks *(WSN)* is crucial. The goal of all WSN application scenarios is to have sensor nodes deployed, unattended, for months or years. In this work, we investigate the problem of energy consumption and lifetime maximizing in a many-to-one sensor network. In such network pattern, all sensor nodes generate and send data to a single sink via multihop transmissions. In our previous experimental studies, we noticed that, since all the sensor data has to be forwarded to a base station via multihop routing, the traffic pattern is highly nonuniform, putting a high burden on the sensor nodes close to the base station. In this paper, we analyze and propose some strategies that balance the energy consumption of these nodes and ensure maximum network lifetime by balancing the load as equally as possible.**

***Index Terms*—Wireless sensor networks, Lifetime maximizing, Energy saving, Load-balancing, Transmission power, Performance evaluation.**

I. INTRODUCTION

Minimizing energy consumption is a key goal in many multihop wireless networking systems, especially when the nodes of the network are battery powered. This requirement has become increasingly important for wireless sensor networks. Wireless sensor networks differ from other types of multihop wireless networks by the fact that, in most cases, the sensor data has to be delivered to a single sink or base station (*BS*). Clearly, one of the primary concerns is the lifetime of the network. Although different definitions of lifetime exist [1], certainly a sensor network has to be considered "dead" whenever it is no longer able to forward any data to the *BS*. We can settle for a definition where network lifetime is the time span from the deployment to the instant when the network is considered nonfunctional. The moment when a network can be considered nonfunctional is, however, application-specific, for example, the instant when the first sensor dies, a percentage of sensors die, or the loss of coverage occurs [2].

In the present paper, we will assume that network lifetime corresponds to the instant when the first node dies. We are also interested in energy balancing strategies to extend sensor network lifetime. Based on load balancing techniques, we derive an optimal solution and propose a heuristic for this problem and compare them to other routing techniques, namely, *equiprobability* and *shortest-path*. The rest of this paper is organized as follows. Related work is discussed in Section II. Section III states the problem of energy-balancing. Section IV contains the problem formulation and the assumptions we made in our study. In Section V, we detail an optimal solution along with other strategies. In Section VI, we take a step back to discuss and compare the proposed strategies. Section VII summarizes the main conclusions of our research, and presents a set of open issues and research challenges.

II. PREVIOUS WORK

There are many energy conservation techniques for WSNs. Anastasi *et al.* provide a good survey in [3]. In order to maximize the sensor network lifetime two major techniques can be employed: the introduction of sleep/active modes for sensors and the use of energy efficient routing. Extensive research has been carried out on energy efficient data gathering and information dissemination in sensor networks. Well-known energy efficient protocols were developed, such as LEACH [4]. LEACH organizes sensor nodes into clusters to fuse data before transmitting to the *BS*. PEGASIS [5] improved the LEACH by considering both metrics of energy consumption and data-gathering delay. Other routing schemes for maximizing network lifetime were presented in [6].

Another important technique used to prolong the lifetime of sensor networks is the introduction of switch on/off modes for sensor nodes. J. Carle *et al.* pointed out in [7] that the best method for conserving energy is to turn off as many sensors as possible, while still keeping the system functioning.

In [8], an analytical model was proposed to derive the upper bound of the sensor network lifetime, given the surveillance region and a *BS*, the number of sensor nodes deployed and initial energy of each node. In [9], authors investigated the upper bounds on network lifetime extension. They illustrated the tradeoff between node density and network lifetime for a cell-based energy conservation technique in wireless ad hoc networks. Along these analytical studies, authors consider different network topologies and they state various assumptions that make any comparison impossible. Other techniques such as random routing proposals exist in the literature. In [10], authors consider a grid topology where each node sends data to all its neighbors with a blind (regardless of destination) routing probability of $\frac{1}{4}$. Slama *et al.* [11] associate a neighborhood discovery protocol with random routing to minimize the overall energy consumption. This problem is NP-complete. Authors propose heuristics for general cases. However, random routing is often tailored to "Mostly-on" functioning where nodes should be "ON" to receive any packet (nodes are subject to idle listening) and involving also overhearing. Our point of view is diametrically opposed as we propose solutions taking

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into account application, topology and sharing the traffic with minimum signaling in order to optimize the network lifetime. In this work we design and analyze several energy balancing strategies in a regular grid topology with uniformly deployed and stationnary nodes. We take into account different transmission power levels to calculate the traffic proportions of each node in order to extend the network lifetime. Furthermore, we derive an optimal solution to balance node energy consumptions and maximize the network lifetime.

III. PROBLEM FORMULATION

The problem can be formulated as follows: Let N be the total number of nodes $\Lambda = (\Lambda_1, \Lambda_2, .., \Lambda_N)$ the vector of output traffic rates of all nodes in the network. The load Λ_i of the node i can be written as follows:

$\Lambda_i = \lambda_i + \sum_j \Lambda_j p_{ji}$, with λ_i as the traffic generated by i itself (we assume that each node generates the same volume λ of traffic from its measures) and p_{ji} is the traffic proportion of traffic sent by node j to i. thus we can write:

$\Lambda = \lambda\mathbb{1} + \Lambda\mathbb{P}$

$\mathbb{1}$ is the identity vector and $\mathbb{P}$ is the stochastic matrix of traffic proportions between the nodes.

$$\mathbb{P} = \begin{pmatrix} p_{11} & p_{12} & .. & p_{1N} \\ p_{21} & p_{22} & .. & p_{2N} \\ .. & .. & .. & .. \\ p_{N1} & p_{N2} & .. & p_{NN} \end{pmatrix}$$

The matrix is obtained under the following constraint: $\sum_{j=1}^{N} p_{ij} = 1$, $\forall i, j \in \{1..N\}^2$

Let q_{ij} be the transmission power between node i and node j. To maximize network lifetime we must minimize the energy consumption of the critical nodes. These are those consuming more energy in the network.

Let E_i be the energy consumed by sensor node i in the network and $E(\mathbb{P}) = (E_1(\mathbb{P}), \ldots, E_N(\mathbb{P}))$ the corresponding vector. We assume that energy consumption for one packet receiving is 1 unit.

$$E_i(\mathbb{P}) = \lambda_i + \sum_j \Lambda_i p_{i,j} q_{i,j}$$

Then the problem is defined as follows:

$$E^* = \min_{\mathbb{P}} \|E(\mathbb{P})\|_\infty \tag{1}$$

This problem is nonlinear with linear constraints. It is solved when the sensors are placed in a grid topology and where the maximum transmission power used q_{ij} is equal to 2. The optimal case can be obtained when the three neighboring nodes of the *BS* (*BS* is placed in the corner of the grid) consume the same energy as we shall demonstrate later.

A. Assumptions

To improve our proposal understanding in the remainder of this paper, we make some reasonable assumptions in the case of a grid network with all-to-sink traffic pattern, as follows:

- Nodes are uniformly distributed in a grid topology with size $N = M\text{x}M$, consequently, the density is uniform throughout the entire network (Fig. 1).

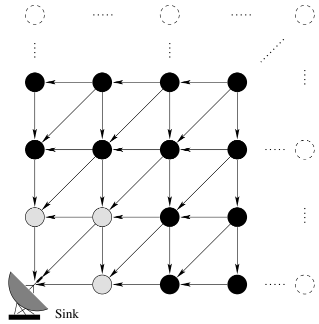


Fig. 1. Sensor network with a regular topology (and *BS* in the corner).

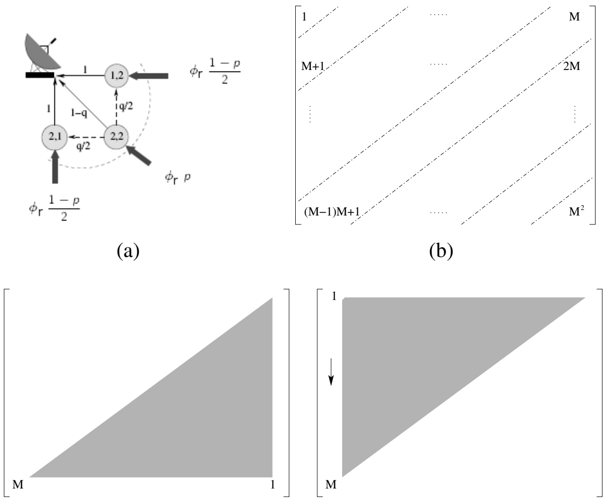
- Each node continuously generates constant bit rate (CBR) data and sends to the *BS* through multihop routes.
- We plan to make a hop by hop routing and load-sharing between the accessible nodes. Indeed, Load sharing is possible without signaling protocol. Basically, we can make calculations early in the life of the network (calculations may be made by the *BS*) and transmit these proportions to the different sensors.
- "Mostly-off" network pattern is better than "Mostly-on" one, that it is why we prefer to refer to proportions rather probabilities because the load-sharing by probabilistic routing is costly and requires "Mostly-on" nodes. Consequently, in "mostly-on" networks, the transmission power has a major impact on the overconsumption of energy due to overhearing.
- Sleep/wakeup scheduling such that there is neither collision nor retransmission.
- Sensor nodes have two different transmission ranges of d and $\sqrt{2}d$ meters.
- According this well-known formula given by [12]: $P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 L d^n}$ we assume that each node use two transmission power levels *TPL*$_1$ for range d and *TPL*$_2$ for $\sqrt{2}d$.
- Since energy consumption (E) when transmitting is proportional to transmission power P_{tx}, (Equation (1) in [13]) we assume: $E(\text{TPL}_2) \simeq 2 \times E(\text{TPL}_1)$

IV. PROBLEM RESOLUTION

Due to the nodes range, the most solicited sensors are those close to the *BS*. Indeed, they will deliver all traffic coming from other nodes, when receiving: $\lambda_r = (N-4)\lambda$; and when transmitting: $\lambda_e = (N-1)\lambda$. Where λ is the generated rate of each node. We note $\phi_r = N - 4$ the rest of the sensor nodes.

Now, let us associate coordinates to each node: (i, j) as in Fig. 2(b). For energy consumption while receiving, the direct neighbors of the *BS* will consume at least: $E = E_{r,min} = (N-4)\lambda$ (reception power has been normalized to 1 unit).

- Let p be the traffic proportion coming directly from "$(2,2)$", and for symmetry reasons, $\frac{1-p}{2}$ the traffic proportion which enters through "$(1,2)$" and "$(2,1)$".
- Let q be the traffic proportion sent by "$(2,2)$" directly to the *BS*, and $\frac{1-q}{2}$ which is sent respectively to "$(1,2)$" and "$(2,1)$".



(a) (b) (c) (d)

Fig. 2. Optimal case analysis.

- Sending message from "$(1,2)$" to "$(2,2)$" has no interest because transmitting from "$(1,2)$" to "$(2,2)$" is as expensive as sending directly to the base station and it will cost certainly to the node "$(2,2)$" itself.

Thus, we look for minimizing the maximum energy consumption of the nodes "$(1,2)$", "$(2,1)$", and "$(2,2)$". Since $E_{(1,2)} = E_{(2,1)}$, the problem is written as follows:

$$\eta^* = \min_{p,q \in (0,1)^2} \max(E_{(1,2)}, E_{(2,2)}) \tag{2}$$

It can easily derived that:

$$p^* = \frac{\phi_r - 1}{4\phi_r};\ q* = 1 \tag{3}$$

With : $\eta^* = E^*_{(1,2)} = E^*_{(2,2)} = \lambda P_1 \{2 + \frac{3(\phi_r - 1)}{4}\}$
This value is a lower bound of E^*. *Can this minimum be reached?* To answer these question, we look for a matrix of proportions that leads to this lower bound. We design a solution where the energy is the same for all nodes located on the same diagonal (Fig. 2(b)). Now, we proceed in the tables below, to the analysis of the traffic and the energy consumption in each diagonal. For information, the energy values in the tables are divided by λ.

Diagonals "1" to "M" above the main diagonal (Fig. 2(c)):

Diag.	Number of nodes	Total receiving	Received per node	Transmitted per node	Energy
1	1	0	0	1	1
..	..	..	..	..	..
k	k	$\frac{k(k-1)}{2}$	$\frac{k-1}{2}$	$\frac{k-1}{2} + 1$	k
..	..	..	..	..	..
M	M	$\frac{M(M-1)}{2}$	$\frac{M-1}{2}$	$\frac{M-1}{2} + 1$	M

The nodes consume at most M.

$$\frac{E_{(1,2)}}{\lambda} = \frac{5 + 3\phi_r}{4} = \frac{3M^2 - 7}{4} > M \ \ if\ M > 2.$$

Diagonals "4" to "$M - 1$" above the main diagonal (Fig. 2(d)):

Diag.	Number of nodes	Total receiving	Received per node	Transmitted per node	Energy
4	..	..	..	..	..
..	..	..	..	..	..
k	k	$M^2 - \frac{k(k+1)}{2}$	$\frac{M^2}{k} - \frac{k+1}{2}$	$\frac{M^2}{k} - \frac{k+1}{2} + 1$	$\frac{2M^2}{k} - k$
..	..	..	..	..	..
M-1	M-1	$M^2 - \frac{M(M-1)}{2}$	$\frac{M^2}{M-1} - \frac{M}{2}$	$\frac{M^2}{M-1} - \frac{M}{2} + 1$	$\frac{2M^2}{M-1} - (M-1)$

$(\frac{2M^2}{k} - k)$ is a decreasing function of k and energy (E) maximum for $k = 4$.

$\frac{2M^2}{4} - 4 = \frac{2M^2-16}{4} < \frac{3M^2-7}{4}$ Therefore, outside the base station range, nodes consuming more energy are those located on the 4^{th} diagonal. They consume less than the nodes within the range.

3^{th} *diagonal:* we are able to find propositions satisfying the equation (3) (Refer to Fig. 3), node $(3,1)$ respectively $(1,3)$ sends to node $(2,1)$ respectively $(1,2)$. We finally obtain:

$E_{(3,1)} = E_{(1,3)} < E_{(2,1)} = \eta^*$
The maximum for $(1,2), (2,1), (2,2)$ is η^*

By applying the calculation rules proposed in the two tables, we obtain the routing proportions illustrated in figure 3, at the same time the matrix $\mathbb{P}$ for which: $E(\mathbb{P}) = \eta^*$ and finally:

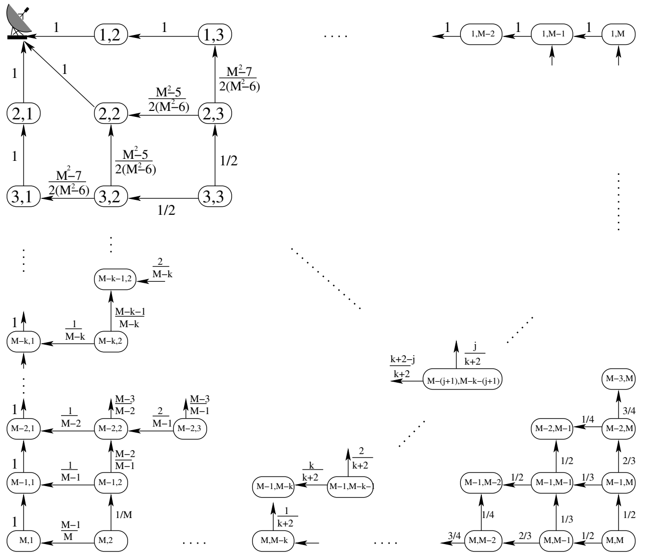


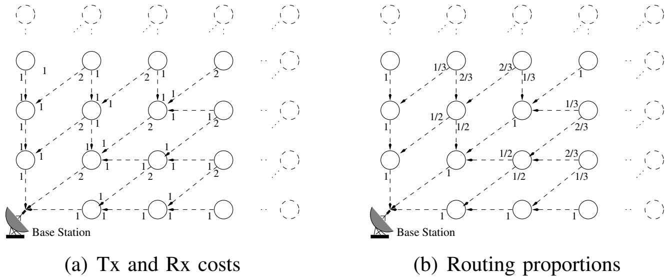
Fig. 3. Stochastic matrix for the optimal solution.

$$E^* = \lambda\left(\frac{3N - 7}{4}\right) \tag{4}$$

V. OTHER EXPLORED STRATEGIES

A. Shortest path routing

A common method to prevent neighbors from consuming energy is to choose the shortest path or share the load between the shortest paths when the node has several shortest paths. In the context of energy balancing the shortest-path are the path that have the lowest cost in terms of energy consumption. However, this involves a first signaling phase to identify these paths and consequently, consume additional energy. In the case of the grid topology shown in Figure 4(a), we notice that the nodes on the two border lines leading to the base station transmit their data always in the direction of their boundary line. While the shortest paths of the rest, is often to take the diagonal link or go to the main diagonal of the grid. Clearly, we can conclude that the most critical node will be the one on the main diagonal close to the base station. Figure 4(a) showing the shortest path algorithm, also shows the emission costs and receiving. We found that the traffic is directed as follows:



(a) Tx and Rx costs

(b) Routing proportions

Fig. 4. Shortest path strategy.

- Nodes on the both sides converging towards the *BS* always send their data in the border direction through the border nodes.
- All the other nodes send their data either in diagonal, they try to reach the main diagonal in the direction of the *BS*.

Furthermore, we must determine for each node the number of the possible shortest paths through each of its neighbors in order to balance the traffic load (Fig. 4(b)).

B. Equiproportional routing

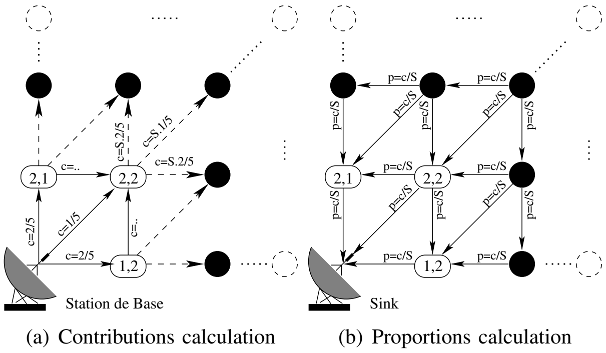
Load balancing may be done with local decision i.e. each node distribute the load equally between the different paths that it has identified to reach the *BS*.

C. Heuristic proposition

The optimal solution being calculable only in special cases, so we propose a heuristic which can be used in broader contexts. We propose a heuristic that attempts to improve the traffic load balancing to increase the lifetime of the network. The principle of this heuristic is to distribute the contributions of each node beginning from the *BS* by considering them as proportional to the transmission power of each node. We consider only the nodes within the same range. The heuristic illustrated in figures 5(a) and 5(b) is described by the following algorithm. We note $V(j)$ the neighborhood of node i and $d(i,j)$ the distance from i to j. In our example, the weight $W(j,i) \propto d^2(j,i)$.

VI. RESULTS AND DISCUSSION

To calculate the consumption of the energy of the "shortest path", "equiproportional" and the "heuristic" strategies, we coded, in C language, the algorithms corresponding to each strategy. In addition to these strategies we have developed a simulated annealing method to approximate the optimum and to find the routing proportions.



(a) Contributions calculation

(b) Proportions calculation

Fig. 5. Load balancing heuristic. (c link contribution and S sum of contributions.)

Algorithm 1 Heuristic of contributions

```
Require: $G(N,A)$, $V = \{v_i\}$, $i \in \Omega$
Ensure: Proportion(i,j)
  {Contributions calculation}
  for all $i \in \Omega$ do
    for all $j \in \Omega$ do
      if $j \in V(i)$ et $d(i,SB) < d(j,SB)$ then
        $Contribution(j,i) \leftarrow SumContributions(i) \times W(j,i)$
        $SumContributions(j) \leftarrow SumContributions(j) + Contribution(j,i)$
      end if
    end for
  end for
  {Proportions calculation}
  for all $j \in \Omega$ do
    $Proportion(i,j) \leftarrow Contribution(i,j)/SumContributions(i)$
  end for
  Return Proportion(i,j)
```

Consumption of the critical nodes: from Fig. 6, we can note that the strategies of the shortest path and that of equiproportional routing are the most consuming, particularly when the number of nodes is very large.

Lifespan: the network lifetime for each strategy can be

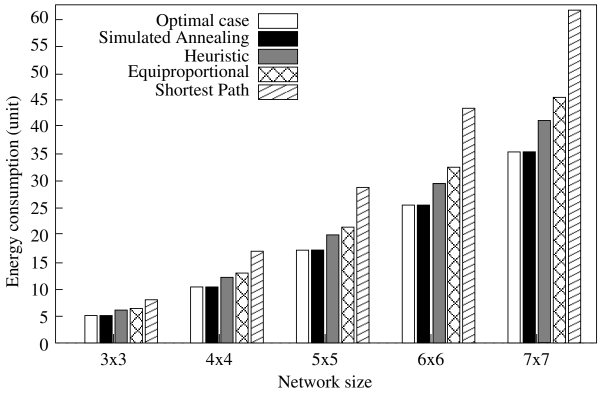


Fig. 6. Energy consumption for $\lambda = 1$.

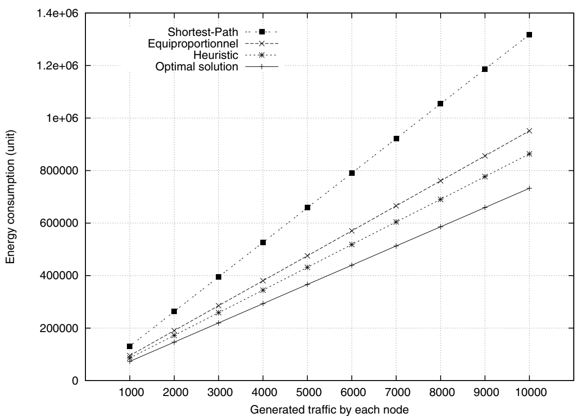


Fig. 7. Maximum energy consumption in a grid of 10 × 10 (*BS* in the corner).

deduced easily from figure 7. In this figure we trace the maximum energy consumed by a node in the network according to the traffic λ generated by each node. We notice that the classical routings do not enable the maximization of the lifespan of the network. Indeed, a shortest path routing has heavy effects on the network lifetime.

A. Case with BS in the center of the grid

We considered also the scenario where the *BS* is placed in the center of the grid. We noted that the traffic load is concentrated on the nodes near to the *BS* and it is distributed symmetrically on the nodes surrounding it. Similarly to the first case (*BS* in the corner of the grid), we compared the strategies of “shortest path” and “equiproportional” routing with the heuristic and the optimal solution that we derived for this case. The optimal solution that we derived with the same approach used in section IV leads to the optimum $E^* = \lambda\left(\frac{3N-13}{10}\right)$. The results are presented in Fig. 8. For a grid topology, the optimal solution gives significant energy consumption enhancement (especially for high load). The gain is deeper for large networks. The shortest path with load balancing consumes much more than equiproportional and the proposed heuristic. Furthermore, lets note that when the *BS* is placed in the center, the energy consumption is reduced significantly (comparing results between Fig. 8 and Fig. 7). It can be a good result for deployment strategies.

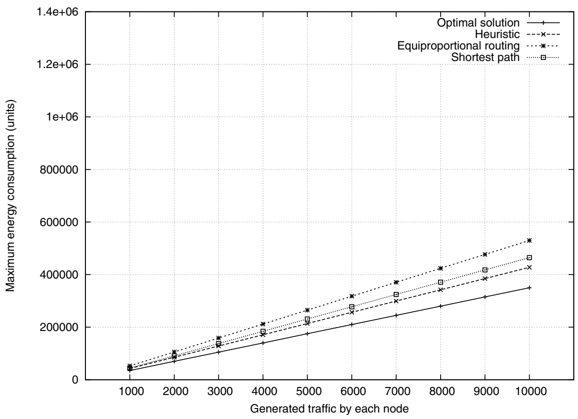


Fig. 8. Maximum energy consumption in a grid of 11 × 11 (*BS* in the center).

VII. CONCLUSION

In this paper, we addressed the network lifetime optimization for the wireless sensor network. We described the design and analysis of several energy balancing methods. For a regular grid topology we derived optimal solution. The position of the *BS* (in the corner) simplifies the optimization problem. Varying the base station position introduce new inequalities constraints to the problem. Indeed, the results that are obtained in this paper confirm the conclusions of our previous experimental studies [14]. It is shown that the optimal network lifetime may be achieved by the proposed methods. These methods may be adapted to different network topologies. The load balancing heuristic is not optimal in the studied case but may be evaluated taking into account additional signaling schemes overheads.

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