Compromis énergie-délai pour la collecte de données dans les réseaux de capteurs

Christelle Caillouet, Tahiry Razafindralambo

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Christelle Caillouet[2] †and Tahiry Razafindralambo[1]

[1] *INRIA Lille - Nord Europe, France*
[2] *RWTH Aachen University, Allemagne*

Les réseaux de capteurs sont utilisés afin de collecter un grand nombre de données de l'environnement. Ces données sont délivrées au travers de l'interface de communication sans fil des capteurs par des communications multi-sauts jusqu'au puits traitant l'information. Le placement de ce puits influe sur les performances des réseaux de capteurs en ce qui concerne le délai et la consommation énergétique, en particulier celle des capteurs intermédiaires servant de relais. L'optimisation de la collecte des données est donc un aspect important dans l'étude des réseaux de capteurs sans fil. Notre article s'interesse à la collecte de données utilisant des puits mobiles. Nous proposons un modèle permettant d'étudier le compromis entre la consommation énergétique du réseau et le délai de collecte des données.

Keywords: optimisation multi-objectif, programmation linéaire, réseaux de capteurs, placement

1 Introduction

Wireless sensor networks (WSNs) have received a lot of attention in recent years due to their potential applications in various areas such as environment monitoring or tracking [BISV08]. In order to get useful and up-to-date information from the environment, the WSN is composed of a large number of low-capacity (processor, memories, battery) sensors. Unfortunately, the amount of data in the network increases with the number of sensors. The data has to be sent to a central entity, called sink, for storage and processing. Thanks to the wireless communication capabilities and the protocols developed, multi-hop transmissions can be used to route data from a sensor to the sink if no direct connection is available. However, this classical N to 1 communication paradigm rapidly consumes the energy of intermediate sensors and provides unfair delay distribution depending on the distance to the sink [KR09]. Data collection is therefore a key issue in WSNs.

Various solutions have been proposed to extend the network lifetime and reduce delay for data collection. In [CCDF09], authors present an integer linear program for placing a minimum number of gateways and ensure connectivity among them and the sink to form a wireless mesh network to deliver the data. The use of mobile sinks instead of static sinks to collect the data is more efficient and significantly increases the lifetime of the WSN [LH05]. In their work, the location of the mobile sinks is periodically computed so that the network lifetime is maximized. Some research efforts have focused on approaches either minimizing the energy consumed by the sensors [GDPV03], or maximizing the global network lifetime [BST09]. Considering the route of the mobile sinks in WSNs instead of its periodical relocation has not been addressed in previous work to the best of our knowledge. Our purpose is to determine where to place a set of gateways to collect the data of a region in the WSN field, and compute the route of a mobile sink moving along the gateways to gather data from the sensors. To answer these questions, we propose a Multiobjective Linear Program (MLP) that allows to study the trade-offs between the length of the route of a mobile sink associated with a computed gateway placement, and the overall energy consumption in a WSN. The main contribution is to give a multi-criteria vision of the data collection problem in WSNs. As far as we know there is no multiobjective analysis in this subject. Unlike the works proposed in the literature, the results of this paper are twofold. First, we tackle the problem of optimal placement of data gateways in an energy-efficient WSN. Second, we optimize the data collection tour by the sink to minimize the delay.

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2 Problem definition

Given a WSN represented by a set of sensor nodes $\mathcal{S}$, we define a set of candidate sites $\mathcal{C_S}$ for the gateway locations. We want each sensor to be associated with its closest gateway : O_i is the vector of ordered reachable gateways for sensor i. If $j < k$, then $dist(i, j) \leq dist(i,k)$ and $O_i(j)$ is before $O_i(k)$ in the vector, where $dist(i, j)$ is the euclidean distance between i and j. Sets $\mathcal{J}_i$ are index sets of vector O_i.

We assume the routing in the WSN (from sensors to gateways) given so that our model is independent of a specific routing strategy. P is the set of paths between the sensors and the candidate sites. $O(p)$ (resp. $\mathcal{D}(p)$) denotes the source node (resp. the destination) of path $p \in P$. From P, we introduce the binary matrix C to indicate the sensor-gateway connectivity : C_{ic} is 1 if it exists a route between sensor i and gateway c.

The energy model considered for the sensors is based on the *first order radio model* described in [HCB00]. A sensor consumes $\varepsilon_{elec} = 50\ nJ/bit$ to run the transmitter or receiver circuitry, $\varepsilon_{amp} = 100\ pJ/bit/m^2$ for the transmitter amplifier. Thus, to receive a k-bit message, sensor i consumes $E_r = \varepsilon_{elec}k$, and $E_t = \varepsilon_{elec}k + \varepsilon_{amp}dist^2(i, j)k$ to transmit this message to a neighbor j.

E_{max} is a decision variable of our MLP corresponding to the amount of energy spent by a sensor. We then have the binary variables x_{ij}, y_j, χ_{ij} indicating respectively if sensor i is assigned to gateway j, if a gateway is installed at candidate site j, and if two gateways are installed at candidate sites i and j and so that link (i, j) is selected for the route of the mobile sink.

To evaluate the overall quality of our solutions, we use the following metrics :

- *MinMaxE (f^1)* : Balancing the energy spent by the sensors, i.e. WSN lifetime maximization. From the energy model presented above, we seek to minimize the maximum energy spent by each sensor node.
- *MinRoute (f^2)* : Minimizing the route of the mobile sink between the different installed gateways.

The optimization problem of placing the gateways such that we jointly minimize the length of the mobile sink route, and the energy spent by the sensor nodes is the following :

$$\begin{cases} \text{(i)}\ \min f^1 = E_{max} \\ \text{(ii)}\ \min f^2 = \sum_{i \in \mathcal{C_S}} \sum_{j \in \mathcal{C_S}} dist(i, j)\chi_{ij} \end{cases} \tag{1}$$

$$\sum_{j \in \mathcal{C_S}} x_{ij} = 1 \qquad \forall i \in \mathcal{S} \tag{2}$$

$$x_{ij} \leq C_{ij} y_j \qquad \forall i \in \mathcal{S}, j \in \mathcal{C_S} \tag{3}$$

$$y_{O_i(k)} + \sum_{h \in \mathcal{J}_i, h > k} x_{iO_i(h)} \leq 1 \qquad \forall i \in \mathcal{S} \tag{4}$$

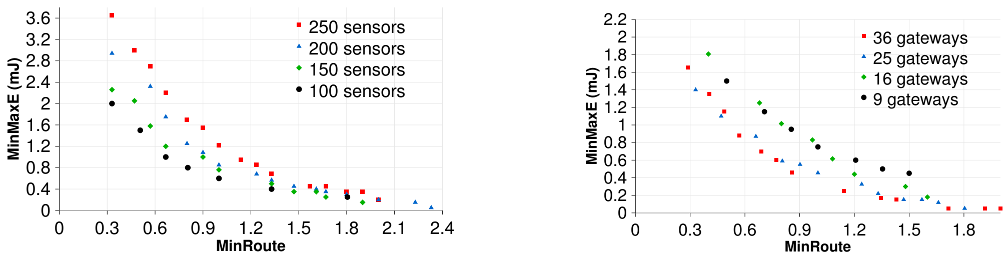
$$\sum_{p \in P,\ i \in p\ |\ i \neq O(p)} (E_r + E_t)\, x_{O(p)\mathcal{D}(p)} + \sum_{p \in P\ |\ i = O(p)} E_t\ x_{i\mathcal{D}(p)} \leq E_{max} \qquad \forall i \in \mathcal{S} \tag{5}$$

$$\sum_{i \in \mathcal{C_S}} \chi_{ij} = y_j,\ \sum_{j \in \mathcal{C_S}} \chi_{ij} = y_i \qquad \forall i, j \in \mathcal{C_S} \tag{6}$$

Obj. (1) minimizes *(i)* the maximum energy consumed by the sensors, and *(ii)* the length of the route of a mobile sink along the placed gateways. Constraints (2) and (3) ensure that each sensor must be associated with an installed gateway. Constraints (4) force each sensor to be assigned to its closest gateway. Constraints (5) minimize the maximum amount of energy spent by the sensors, i.e. the sum of the forwarded traffic from other sensors and its own traffic. Equalities (6) force the mobile sink to visit all the chosen gateways to collect data generated by the sensors.

3 Performance evaluation

We present results obtained with our MLP on networks of size between 50 and 250 sensors in which the sensor's position is randomly chosen in a unitary square area. We use two policies of candidate site locations. First, we divide the area into equal squares and place one candidate site in the center of each square. In this way, the candidate sites form a regular grid. Second, we choose randomly the location of the candidate sites in the area. We solved the proposed MLP with these instances using IBM Cplex solver on an INTEL Core 2 2.4 GHz with 2 Gb of memory. Each result has been averaged on 10 instances.



(a) Different size and $|\mathcal{C}_\mathcal{S}| = 9$.

(b) Different number of candidate sites and $|\mathcal{S}| = 50$.

FIGURE 1: Pareto fronts obtained for the random networks tested.

Combining the two metrics of our MLP is not relevant. Indeed, there exists confliction between route length and energy consumption, i.e., pursuing the optimization of the route length of the mobile sink inextricably damages the performance of energy spent by the sensors. Saving energy enforces to deploy more gateways in the network, thus increasing the length of the route for the mobile sinks. The main idea to study the trade-offs between *MinMaxE* and *MinRoute* is to find out the possible non-dominated solutions of the multi-objective optimization problem. A solution is non-dominated if it is not possible to improve one of the metrics without worsening at least one another. The set of non-dominated solutions is the *Pareto front*, that provides a set of solutions that can be chosen depending on the application requirements. In order to generate solutions on the Pareto front, we use the ε-constraint method that transforms the multiobjective problem into a sequence of parameterized single-objective problems such that the optimum of each single-objective problem corresponds to a Pareto-optimal solution.

3.1 Effect of candidate sites and network density

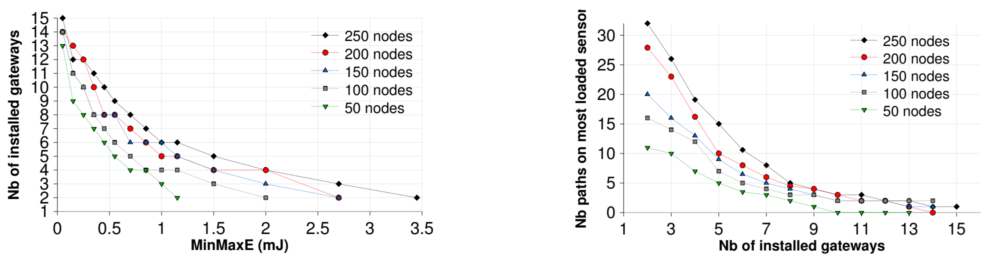
Limiting the energy spent by each sensor increases the length of the mobile sink route (see Fig. 1(b) and 1(a)). Moreover, the number of installed gateways strongly depends on the limit of the energy spent. In particular, when we focus on energy (optimizing only *MinMaxE*, without any constraints on the number of deployed gateways) the optimal solution minimizes the energy spent by each sensor essentially by limiting its forwarding traffic. The gateway placement thus verifies that each sensor is a neighbor of its associated gateway (when possible). When the size of the network increases, then the energy consumption of the sensor nodes also increases (see Fig. 1(a)). The total traffic is more important, so the sensors have more forwarding traffic to relay which increases their load. When the energy is limited to $E_{max} = 2$ mJ for each sensor, the length of the mobile sink route also increases with the network size. The average route length of the mobile sink equals respectively $0.33,\ 0.47,\ 0.6$, and 0.65 for a WSN of $100,\ 150,\ 200$, and 250 nodes. However, the maximum amount of energy spent by the sensor nodes decreases when the number of candidate sites in the network increases as depicted in Fig. 3. On one hand, placing a gateway reduces the relaying traffic and the energy spent. On the other hand, the route length of the mobile sink increases, especially when the energy consumed by each sensor is low. This assertion is confirmed by Fig. 4 that depicts the number of deployed gateways depending on the maximum energy spent by the sensors. The location of the gateways among the WSN is also important regarding the network lifetime and the delay of data collection.

3.2 Sensor's load

We define the sensor's load as the number of paths going through a sensor : $Load(i) = \sum_{p\in\mathcal{P}|i\in p} x_{\mathcal{O}(p)\mathcal{D}(p)}$, $\forall i \in \mathcal{S}$. The most loaded sensor is therefore the one that has the maximum number paths going through it : $Load(\mathcal{S}) = \max_{i\in\mathcal{S}} Load(i)$. Fig.4 presents the value of $Load(\mathcal{S})$ in function of the number of deployed gateways. This confirms that deploying more gateways allows to limit the amount of forwarding traffic at each sensor. Another way of limiting the sensor's load is to fairly deploy the gateways among the WSN. When the candidate sites are regularly placed in the area (i.e. the regular policy), then the load is reduced in comparison to a random placement (see Table 1). $\overline{Load(\mathcal{S})}$ is the mean value $Load(\mathcal{S})$ over the Pareto

Topology		Grid placement				Random placement			
$\lvert\mathcal{S}\rvert$	$\lvert\mathcal{C}_\mathcal{S}\rvert$	f^{1*} (mJ)	f^{2*}	$\overline{Dpl.\ Gtw}$	$\overline{Load(\mathcal{S})}$	f^{1*} (mJ)	f^{2*}	$\overline{Dpl.\ Gtw}$	$\overline{Load(\mathcal{S})}$
50	9	0.45	0.5	3.5	8.93	0.45	0.21	2.96	13.24
50	16	0.15	0.4	4.25	8	0.35	0.22	4.63	9.83
100	9	0.45	0.5	3.33	10.2	0.65	0.28	3.71	21.26
100	16	0.35	0.4	4.81	9.87	0.65	0.21	4	21
150	9	0.75	0.5	2.85	17	0.95	0.08	3.05	27.88
150	16	0.45	0.4	4.24	12.76	0.75	0.01	4.41	20.53
200	9	0.85	0.5	3.9	16.3	0.95	0.22	3.17	20.79
200	16	0.25	0.4	4.77	13.5	1.05	0.11	3.53	27.4

TABLE 1: Comparison between regular and random placement for the candidate sites.



(a) Deployed gateways vs. E_{max}.

(b) Sensors load vs. gateways.

FIGURE 2: Results for random networks with 25 candidate sites.

optimum. This value is always greater when the gateway placement is performed among candidate sites chosen randomly, leading to more loaded sensors.

4 Conclusion

In this paper, we present a framework for efficient data collection in WSNs. We develop a multi-objective linear program with two functions to evaluate the trade-off between the energy spent by the sensors, and the length of the route of mobile sinks collecting data at gateways that we jointly deploy. We show that the sensors' load decreases with the number of gateways until a given threshold when it remains stable. This allows to save energy in the WSN, but, when the number of deployed gateways is important, the mobile sink has a longer route to perform, therefore increasing the delay of data collection until processing. This trade-off must be taken into consideration for an optimal WSN design. Our work provides solutions that allow decision makers to optimally design the data collection plan in WSN with mobile sinks.

Références

[BISV08] G. Barrenetxea, F. Ingelrest, G. Schaefer, and M. Vetterli. The hitchhiker's guide to successful wireless sensor network deployments. In *ACM SenSys*, pages 43–56, 2008.

[BST09] L. Ben Saad and B. Tourancheau. Multiple mobile sinks positioning in wireless sensor networks for buildings. In *SENSORCOMM*, pages 264–270, 2009.

[CCDF09] A. Capone, M. Cesana, D. Donno, and I. Filippini. Optimal placement of multiple interconnected gateways in heterogeneous wireless sensor networks. In *IFIP-TC 6 Networking Conference*, pages 442–455, 2009.

[GDPV03] S.R. Gandham, M. Dawande, R. Prakash, and S. Venkatesan. Energy efficient schemes for wireless sensor networks with multiple mobile base stations. In *IEEE GlobeCom*, pages 377–381, 2003.

[HCB00] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocol for wireless micro sensor networks. In *HICSS*, pages 3005–3010, 2000.

[KR09] F. Khadar and T. Razafindralambo. Performance evaluation of gradient routing strategies for wireless sensor networks. In *IFIP-TC6 Networking Conference*, pages 535–547, 2009.

[LH05] J. Luo and J.-P. Hubaux. Joint mobility and routing for lifetime elongation in wireless sensor networks. In *IEEE INFOCOM*, pages 1735 – 1746, 2005.