Economie d'énergie dans les protocoles de population

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[1] *LRI, Université Paris Sud, CNRS, Université Paris Saclay, France, {joffroy.beauquier, janna.burman, chuan.xu@lri.fr}*

Dans cet article, pour la première fois (à notre connaissance), un modèle formel de consommation d'énergie est proposé pour les *protocoles de populations* (PP). Ceux-ci représentent des réseaux de capteurs asynchrones, passivement mobiles et anonymes. Le modèle d'énergie proposé pour PP permet l'étude analytique de la consommation d'énergie en tant que paramètre de complexité. A titre d'application, nous étudions la complexité en énergie pour le problème de la *collecte de données*. Nous présentons un protocole (*EB-$TTFM$*) qui est efficace pour cette complexité sous certaines conditions. Enfin, nous donnons une borne inférieure de la complexité en énergie pour la collecte de données, qui justifie l'efficacité d'*EB-$TTFM$*.

Mots-clefs : réseaux de capteurs mobiles, protocoles de populations, consommation d'énergie, collecte de données

1 Introduction

Inspired by *population protocols* (PP) [AAD+06], with anonymous and uniformly bounded memory mobile sensors (called agents) interacting in pairs, we propose an enhanced model which considers energy consumption for interacting and detecting other agents in proximity (Sect. 2). The interest of this extended model is to allow a purely analytical analysis of the energy complexity of a protocol without simulations.
In order to illustrate its power and its usefulness, we consider the issue of determining the amount of agents' initial energy necessary and sufficient for being able to perform a given task. In this context, the natural chosen metric is the maximum energy spent by an agent (for accomplishing the overall collaborative task). It is particularly important in the case of networks where it is difficult or undesirable to access the sensors frequently (cf., Bird Species Recognition [BMDT16]). Due to the nature of the considered problem, a worst case analysis has to be done. However, if no guarantees are imposed on the agents' interactions, such analysis is in general impossible (for non-trivial protocols). Consider, for example, one of the classical assumptions in PP where any pair of agents is required to interact only infinitely often. In this case, protocols converge only eventually, consuming an arbitrary energy till convergence.
To avoid this phenomenon and being able to perform a worst case analysis, we assume a sort of partial synchrony, proposed in [BBCK10], according to which an agent interacts with all the others with a certain "frequency", expressed by a *cover time* parameter. This is an upper bound on the "time", counted in the number of global interactions (pairwise meetings), for an agent to interact with all the others. As shown by recent experimental and analytical studies, cf. [HRK+08], such assumption of bounded cover times may well model the mobility in many practical sensor networks (e.g., where agents have different communication capabilities, and move within a bounded area).

To illustrate the proposed model, we study *data collection*, which is known to be a fundamental task in sensor networks. Each sensor has got a value from the environment (temperature, pressure, altitude, etc.), and eventually all the values must be routed towards a *base station* (BST), where they will be analyzed and treated. Transfers of values between sensors are possible in order to optimize time and energy metrics. In this context, our first contribution is the energy complexity analysis of an already known time optimal protocol (Sect. 3). The second contribution is a new power-aware protocol, which improves the previous one in terms of the maximum energy spent by an agent (Sect. 4). Finally, we present a lower bound concerning energy consumption of any possible data collection protocol and we show the cases where this lower bound is reached by the presented protocols (Sect. 5). Refer to [BBX17] for the complete version of this article.

2 Model and Notations

A system consists of a collection $\mathcal{A}$ of n pairwise interacting anonymous agents (n is unknown to the agents). Among the agents, there is a distinguishable agent, BST, which has unbounded memory and resources, in contrast with the other agents with uniformly bounded memory. We adopt the usual definitions for the system: *state* of an agent, *configuration* (a vector of all the agents' states), *transition* (an atomic step in which two interacting agents exchange and update their states according to a protocol), *execution* (a sequence of configurations where each next configuration is obtained by a transition from the previous one).

Cover Time Fairness. Every agent $i \in \mathcal{A}$ has an *unknown* to agents parameter $cv_i \in \mathcal{N}$, called *cover time* s.t. during any cv_i time units (consecutive interactions in an execution), agent i interacts with every other agent at least once. For two agents x and y, if $cv_x < cv_y$, then we say that x is *faster* than y, and y is *slower* than x. We assume that two interacting agents can only compare their respective cvs (see [BBCK10] for an example of how it can be implemented). The minimum cover time value is denoted by cv_{min} and the maximum one by cv_{max}. A *fastest* (resp. *slowest*) agent z has $cv_z = cv_{min}$ (resp. $cv_z = cv_{max}$). We denote by F the set of fastest non-BST agents, and by NF the set of non-fastest ones. In the protocol analysis, we sometimes assume that $cv_{min} \gg O(n^2)$, i.e., cv_{min} is much larger than the number of all the possible pair-wise interactions. Under this assumption, agents are free to interact in different ways, which is natural for the passively mobile sensor networks modeled by PP.

Data Collection. We assume that each agent, except BST, owns initially an input value (which is constant during one execution of the protocol). Eventually, every input value has to be delivered to BST, and exactly once (as a multi-set). When this happens, we say that the protocol has converged. The convergence time of a protocol is the maximum length of a possible execution (until convergence). We denote by M the number of values that a non-BST agent can receive from other agents (on top of its own initial value). When describing or analyzing a considered protocol, the term "to transfer a value" from agent x to y means to copy it to y's memory, and erase it from the memory of x.

Energy Consumption Scheme and Metrics. Each agent starts with the same amount of initial energy E_0 (e.g., all agents are fully charged). It is in *sleep* mode and consumes E_{slp} per time unit (every interaction). When two agents in *sleep* mode interact, both of them turn into *awake* mode and each consumes E_{wkp} energy. This energy does not depend on the size of the transmitted data. This is justified by the fact that agents in *PP* have a small uniformly bounded memory and thus any communication would fit in very few packets. During an interaction, two *awake* agents decide to turn either to *sleep* or to *terminated* mode, according to the protocol. No energy is consumed by a terminated agent. We assume that when a sleeping agent x meets a *terminated* agent y (detects it by its proximity sensor), x wakes up and consumes E_{wkp}, because it has to interact to detect the mode of y. For detailed explanations and the motivation for this energy consumption scheme, please refer to the technical report [BBX17].

In this work, we choose to evaluate and minimize the maximum energy spent per node across the network in each data collection, thereby enhancing the lifetime performance. Given a protocol $\mathcal{P}$, we denote by $Es_{max}(\mathcal{P})$ the maximum energy spent by an agent in all executions of $\mathcal{P}$. This metric is one of the most popular metrics studied in power-aware routing protocols for MANET [SWR98]. Minimizing it can be also seen as balancing the distribution of energy consumption among agents.

3 Energy Consumption of $TTFM$

In this section, we consider an existing protocol, which was designed without energy consumption in mind, and we perform its energy consumption analysis, using the defined energy model. $TTFM$ (Transfer To the Faster Marked) is a time-optimal protocol for data collection in PP [BBCK10]. The basic strategy for data transfer, is that a non-BST agent only transfers its values either to BST, or to other agents which have never met any other agent faster than themselves. The idea of $TTFM$ is to make use of the fastest agents (recall that a fastest agent "does not know" it is fastest), which are more likely to bring the values sooner to BST. As a preliminary step, we adapt $TTFM$ such that a non-BST agent turns into *terminated* mode once it has transferred its values to a faster agent (excluding BST). This adapted protocol, called $E\text{-}TTFM$, is presented below.

$E\text{-}TTFM$ has the same *time* complexity as $TTFM$, because the adaption we did does not influence the

Protocol 1: *E-TTFM* (for a mobile agent *i* interacting with an agent *j*)

Data: $fastest\_mark_i \in \{0,1\}$ (* initialized to 1 *)
if *j is not BST* **then**
  if $cv_j < cv_i \wedge fastest\_mark_j := 1$ **then** $fastest\_mark_i := 0$;
  if $fastest\_mark_j > fastest\_mark_i \wedge$ *there is a free place in j's memory* **then**
    agent *i* transfers to *j* as many values as it would fit in the free part of *j*'s memory;
    if *agent i has no value in its memory* **then** agent *i* turns into *terminated* mode ;
if *j is BST* **then** agent *i* transfers all values to BST ;

worst case convergence time of data collection. Therefore, the longest execution in *E-TTFM* is of length $2cv_{min}\lceil\frac{|NF|}{M|F|}\rceil - 1$ (Th. 11 in [BBCK10]). The worst case on the maximum energy spent by an agent is attained in the longest execution in which one fastest agent participates in a maximum number of interactions (being in *awake* mode as long as possible). This implies the following result :

Proposition 1 *An upper bound on the maximum energy spent by an agent in E-TTFM is* $(2cv_{min}\lceil\frac{|NF|}{M\times|F|}\rceil - 1)E_{wkp}$. *This bound is reached when* $cv_{min} \gg O(n^2)$.

4 Energy-Balanced Protocol *EB-TTFM*

A first step towards an energy efficient protocol would be to consider the following strategy. When an agent notices that it becomes very "low" in energy, it tries to transfer its values to a more powerful agent, as soon as possible. The issue raised by this strategy is that the convergence time of data collection could possibly be considerably augmented, especially if some values are transferred to a slow agent. An increased convergence time means more energy spent by the agents, in general.
Therefore, the level of the amount of residual energy that is considered to be "low" should be carefully set. Below, we discuss the possible choices of such a level of residual energy. We make these choices depend on a parameter λ, by defining the "low" level by $\frac{E_0}{\lambda}$, where $\lambda \geq 1$ †. Adding the test of the energy level to *E-TTFM* yields a protocol that we name *EB-TTFM* (for Energy Balanced *TTFM*). Let el_i be the residual energy of the mobile agent *i*.

Protocol 2: *EB-TTFM*(λ) (for a mobile agent *i* interacting with an agent *j*)

1 **if** *j is not BST* **then**
2   **if** $el_i < \frac{E_0}{\lambda} \wedge el_i < el_j \wedge$ *there is a free place in j's memory* **then**
3   agent *i* transfers to *j* as many values as it would fit in the free part of *j*'s memory;
4   **if** *agent i has no value in its memory* **then** agent *i* turns into *terminated* mode ;
5   **else** execute *E-TTFM* ;
6 **if** *j is BST* **then** agent *i* transfers all values to BST ;

Here, due to the lack of space, we present the results for the case where the memory is non-bounded, i.e., $M \geq n-1$. For the results on the case of bounded memory, please refer to the technical report [BBX17].
Now, notice that $E_0 - \frac{E_0}{\lambda} = \frac{\lambda-1}{\lambda}E_0$ represents a lower bound on the amount of energy consumed by an agent *i* executing line 2. If this lower bound is too large, *E-TTFM* is always executed (line 5). While when this lower bound is too small, the protocol convergence (and also the energy consumption) depends on the cover time of a slowest agent. Th. 1 gives an upper bound for Es_{max} considering the other more interesting cases. We denote by θ the ratio between E_{slp} and E_{wkp} ($\theta = E_{slp}/E_{wkp} < 1$).

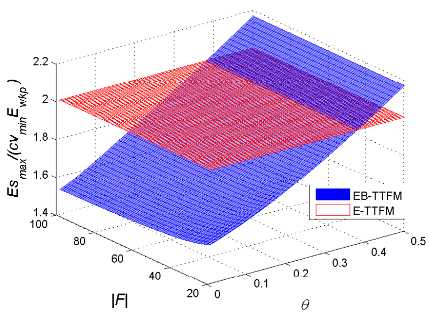
Theorem 1 [Worst Case Energy Analysis when $M \geq n-1$] *If* $(\frac{\theta}{1-(1-\theta)^{\lceil\frac{|F|}{2}\rceil}})cv_{min}E_{wkp} \leq \frac{\lambda-1}{\lambda}E_0 \leq (2cv_{min} - 1)E_{wkp}$, *then* $Es_{max}(EB\text{-}TTFM) \leq \frac{\lambda-1}{\lambda}E_0 + (1+\frac{1}{2-\theta})cv_{min}E_{wkp} = \Theta(cv_{min}E_{wkp})$.

Best Choice for λ. Now, given E_0 (large enough for accomplishing the task), we study the best choice for λ for minimizing $Es_{max}(EB\text{-}TTFM)$. We can see from Th. 1 that $Es_{max}(EB\text{-}TTFM)$ decreases when λ decreases. But λ has to satisfy the condition $E_0 \geq \frac{\lambda}{\lambda-1}(\theta/(1-(1-\theta)^{\lceil\frac{|F|}{2}\rceil}))cv_{min}E_{wkp}$. Therefore, the smallest

†. To conform with the finite state population protocol model, we assume that $\frac{E_0}{\lambda}$ can only take a finite number of values.

value of λ is obtained when $\frac{\lambda}{\lambda-1}(\frac{\theta}{1-(1-\theta)^{\lceil\frac{|F|}{2}\rceil}})cv_{min}E_{wkp} = E_0$, which is $\tilde{\lambda} = E_0/(E_0 - (\frac{\theta}{1-(1-\theta)^{\lceil\frac{|F|}{2}\rceil}})cv_{min}E_{wkp})$.

Interpretation of Results: **comparing energy performances of** ***EB-TTFM*** **and** ***E-TTFM*****.** Now, we give a meaningful example of the interest to have analytical functions for describing the energy consumption performance. This example considers the unbounded memory case and illustrates conditions under which *EB-TTFM* outperforms *E-TTFM*.



When the memory is not bounded and $cv_{min} \gg O(n^2)$, by Prop. 1, $Es_{max}(E\text{-}TTFM) = (2cv_{min} - 1)E_{wkp}$, and by Th. 1, when λ is set to $\tilde{\lambda}$, $Es_{max}(EB\text{-}TTFM(\tilde{\lambda})) \leq (1 + \theta/(1-(1-\theta)^{\lceil\frac{|F|}{2}\rceil}) + \frac{1}{2-\theta})cv_{min}E_{wkp}$. Then, we obtain that for $|F| \geq 10$ and $\theta \leq (3-\sqrt{5})/2 \approx 0.38$, $Es_{max}(EB\text{-}TTFM(\tilde{\lambda})) \leq Es_{max}(E\text{-}TTFM)$, i.e., $EB\text{-}TTFM(\tilde{\lambda})$ outperforms *E-TTFM*. The figure to the left represents the comparison of Es_{max} between $EB\text{-}TTFM(\tilde{\lambda})$ and *E-TTFM* with different $|F|$ and θ. The red (lighter) plane shows $Es_{max}(E\text{-}TTFM)$ and the blue (darker) one represents $Es_{max}(EB\text{-}TTFM(\tilde{\lambda}))$. We can see that $EB\text{-}TTFM(\tilde{\lambda})$ is more energy efficient when θ is small, i.e., when the energy spent in *sleep* mode is much less than the energy spent in *awake* mode.

5 Lower Bound on Es_{max}

In this section, we present a lower bound (Th. 2) on the maximum energy spent by an agent for data collection. The protocols considered here, like in the whole study, are those that can only compare cover times and the residual energies of any two interacting agents. Let us denote this class of protocols by $\mathbf{P}^{cv\cup e}$.

Theorem 2 **[Lower Bound on Es_{max} for Protocols in $\mathbf{P}^{cv\cup e}$]** *If $cv_{min} \gg O(n^2)$, for any protocol in $\mathbf{P}^{cv\cup e}$, the energy spent by an agent in the worst case is at least* $\max\{Es_{max}(E\text{-}TTFM)/\lceil\frac{|F|}{2}\rceil, cv_{min}E_{wkp}\}$.

Next, we identify the cases where this bound is reached by the presented protocols (Cor. 1), and where it differs only by a constant multiplicative factor from the energy complexity of *EB-TTFM*, for the case of non-bounded memory and with a good choice of λ (Cor. 2).

Corollary 1 *When $|F| \leq 2$ and $cv_{min} \gg O(n^2)$, E-TTFM is optimal in $\mathbf{P}^{cv\cup e}$, with respect to the energy spent by an agent in the worst case.*

Corollary 2 *When $|F| > 2$ and $cv_{min} \gg O(n^2)$, for any protocol in $\mathbf{P}^{cv\cup e}$, the energy spent by an agent in the worst case is at least $cv_{min}E_{wkp}$. For the case where $M \geq n-1$ and λ satisfies the conditions of Th. 1, $EB\text{-}TTFM(\lambda)$ reaches this bound asymptotically.*

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