Coverage and Lifetime Optimization in Heterogeneous Energy Wireless Sensor Networks

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Abstract—**One of the fundamental challenges in Wireless Sensor Networks (WSNs) is the coverage preservation and the extension of the network lifetime continuously and effectively when monitoring a certain area (or region) of interest. In this paper, a coverage optimization protocol to improve the lifetime in heterogeneous energy wireless sensor networks is proposed. The area of interest is first divided into subregions using a divide-and-conquer method and then the scheduling of sensor node activity is planned for each subregion. The proposed scheduling considers rounds during which a small number of nodes, remaining active for sensing, is selected to ensure coverage. Each round consists of four phases: (i) Information Exchange, (ii) Leader Election, (iii) Decision, and (iv) Sensing. The decision process is carried out by a leader node, which solves an integer program. Simulation results show that the proposed approach can prolong the network lifetime and improve the coverage performance.**

Keywords-Area Coverage, Network lifetime, Optimization, Scheduling, Distributed Protocol.

I. INTRODUCTION

The fast developments in the low-cost sensor devices and wireless communications have allowed the emergence the WSNs. WSN includes a large number of small , limited-power sensors that can sense, process and transmit data over a wireless communication . They communicate with each other by using multi-hop wireless communications , cooperate together to monitor the area of interest, and the measured data can be reported to a monitoring center called, sink, for analysis it [1], [2]. There are several applications used the WSN including health, home, environmental, military,and industrial applications [3]. The coverage problem is one of the fundamental challenges in WSNs [4] that consists in monitoring efficiently and continuously the area of interest. The limited energy of sensors represents the main challenge in the WSNs design [1], where it is difficult to replace and/or recharge their batteries because the the area of interest nature (such as hostile environments) and the cost. So, it is necessary that a WSN deployed with high density because spatial redundancy can then be exploited to increase the lifetime of the network . However, turn on all the sensor nodes, which monitor the same region at the same time leads to decrease the lifetime of the network. To extend the lifetime of the network, the main idea is to take advantage of the overlapping sensing regions of some sensor nodes to save energy by turning off some of them during the sensing phase [5]. WSNs require energy-efficient solutions to improve the network lifetime that is constrained by the limited power of each sensor node [3]. In this paper, we concentrate on the area coverage problem, with the objective of maximizing the network lifetime by using an adaptive scheduling. The area of interest is divided into subregions and an activity scheduling for sensor nodes is planned for each subregion. In fact, the nodes in a subregion can be seen as a cluster where each node sends sensing data to the cluster head or the sink node. Furthermore, the activities in a subregion/cluster can continue even if another cluster stops due to too many node failures. Our scheduling scheme considers rounds, where a round starts with a discovery phase to exchange information between sensors of the subregion, in order to choose in a suitable manner a sensor node to carry out a coverage strategy. This coverage strategy involves the solving of an integer program, which provides the activation of the sensors for the sensing phase of the current round.

The remainder of the paper is organized as follows. The next section reviews the related work in the field. Section III is devoted to the scheduling strategy for energy-efficient coverage. Section IV gives the coverage model formulation, which is used to schedule the activation of sensors. Section V shows the simulation results obtained using the discrete event simulator OMNeT++ [6]. They fully demonstrate the usefulness of the proposed approach. Finally, we give concluding remarks and some suggestions for future works in Section VI.

II. RELATED WORKS

This section is dedicated to the various approaches proposed in the literature for the coverage lifetime maximization problem, where the objective is to optimally schedule sensors' activities in order to extend network lifetime in a randomly deployed network. As this problem is subject to a wide range of interpretations, we have chosen to recall the main definitions and assumptions related to our work.

A. Coverage

The most discussed coverage problems in literature can be classified into two types [7]: area coverage (also called full or blanket coverage) and target coverage. An area coverage problem is to find a minimum number of sensors to work, such that each physical point in the area is within the sensing range of at least one working sensor node. Target coverage problem is to cover only a finite number of discrete points called targets. This type of coverage has mainly military applications. Our work will concentrate on the area coverage by design and implementation of a strategy, which efficiently selects the active nodes that must maintain both sensing coverage and network connectivity and at the same time improve the lifetime of the wireless sensor network. But, requiring that all physical points of the considered region are covered may be too strict, especially where the sensor network is not dense. Our approach represents an area covered by a sensor as a set of primary points and tries to maximize the total number of primary points that are covered in each round, while minimizing overcoverage (points covered by multiple active sensors simultaneously).

B. Lifetime

Various definitions exist for the lifetime of a sensor network [8]. The main definitions proposed in the literature are related to the remaining energy of the nodes or to the coverage percentage. The lifetime of the network is mainly defined as the amount of time during which the network can satisfy its coverage objective (the amount of time that the network can cover a given percentage of its area or targets of interest). In this work, we assume that the network is alive until all nodes have been drained of their energy or the sensor network becomes disconnected, and we measure the coverage ratio during the WSN lifetime. Network connectivity is important because an active sensor node without connectivity towards a base station cannot transmit information on an event in the area that it monitors.

C. Activity scheduling

Activity scheduling is to schedule the activation and deactivation of sensor nodes. The basic objective is to decide which sensors are in what states (active or sleeping mode) and for how long, so that the application coverage requirement can be guaranteed and the network lifetime can be prolonged. Various approaches, including centralized, distributed, and localized algorithms, have been proposed for activity scheduling. In distributed algorithms, each node in the network autonomously makes decisions on whether to turn on or turn off itself only using local neighbor information. In centralized algorithms, a central controller (a node or base station) informs every sensors of the time intervals to be activated.

D. Distributed approaches

Some distributed algorithms have been developed in [9], [10], [11], [12], [13] to perform the scheduling. Distributed algorithms typically operate in rounds for a predetermined duration. At the beginning of each round, a sensor exchanges information with its neighbors and makes a decision to either remain turned on or to go to sleep for the round. This decision is basically made on simple greedy criteria like the largest uncovered area [14], maximum uncovered targets [15]. In [10], the scheduling scheme is divided into rounds, where each round has a self-scheduling phase followed by a sensing phase. Each sensor broadcasts a message containing the node ID and the node location to its neighbors at the beginning of each round. A sensor determines its status by a rule named off-duty eligible rule, which tells him to turn off if its sensing area is covered by its neighbors. A back-off scheme is introduced to let each sensor delay the decision process with a random period of time, in order to avoid simultaneous conflicting decisions between nodes and lack of coverage on any area. [16] defines a model for capturing the dependencies between different cover sets and proposes localized heuristic based on this dependency. The algorithm consists of two phases, an initial setup phase during which each sensor computes and prioritizes the covers and a sensing phase during which each sensor first decides its on/off status, and then remains on or off for the rest of the duration. Authors in [17] propose a novel distributed heuristic named Distributed Energy-efficient Scheduling for k-coverage (DESK) so that the energy consumption among all the sensors is balanced, and network lifetime is maximized while the coverage requirement is being maintained. This algorithm works in round, requires only 1-sensing-hop-neighbor information, and a sensor decides its status (active/sleep) based on its perimeter coverage computed through the k-Non-Unit-disk coverage algorithm proposed in [18].

Some other approaches do not consider a synchronized and predetermined period of time where the sensors are active or not. Indeed, each sensor maintains its own timer and its wake-up time is randomized [11] or regulated [19] over time.

E. Centralized approaches

Power efficient centralized schemes differ according to several criteria [20], such as the coverage objective (target coverage or area coverage), the node deployment method (random or deterministic) and the heterogeneity of sensor nodes (common sensing range, common battery lifetime). The major approach is to divide/organize the sensors into a suitable number of set covers where each set completely covers an interest region and to activate these set covers successively.

The first algorithms proposed in the literature consider that the cover sets are disjoint: a sensor node appears in exactly one of the generated cover sets. For instance, Slijepcevic and Potkonjak [21] propose an algorithm, which allocates sensor nodes in mutually independent sets to monitor an area divided into several fields. Their algorithm builds a cover set by including in priority the sensor nodes, which cover critical fields, that is to say fields that are covered by the smallest number of sensors. The time complexity of their heuristic is $O(n^2)$ where n is the number of sensors. In [22], a graph coloring technique is described to achieve energy savings by organizing the sensor nodes into a maximum number of disjoint dominating sets, which are activated successively. The dominating sets do not guarantee the coverage of the whole region of interest. Abrams et al. [23] design three approximation algorithms for a variation of the set k-cover problem, where the objective is to partition the sensors into covers such that the number of covers that includes an area, summed over all areas, is maximized. Their work builds upon previous work in [21] and the generated cover sets do not provide complete coverage of the monitoring zone.

In [24], the authors propose a heuristic to compute the disjoint set covers (DSC). In order to compute the maximum number of covers, they first transform DSC into a maximum-flow problem, which is then formulated as a mixed integer programming problem (MIP). Based on the solution of the MIP, they design a heuristic to compute the final number of covers. The results show a slight performance improvement in terms of the number of produced DSC in comparison to [21], but it incurs higher execution time due to the complexity of the mixed integer programming solving. [24] propose a method to efficiently compute the maximum number of disjoint set covers such that each set can monitor all targets. They first transform the problem into a maximum flow problem, which is formulated as a mixed integer programming (MIP). Then their heuristic uses the output of the MIP to compute disjoint set covers. Results show that this heuristic provides a number of set covers slightly larger compared to [21] but with a larger execution time due to the complexity of the mixed integer programming resolution. Zorbas et al. [25] present B{GOP}, a centralized coverage algorithm introducing sensor candidate categorization depending on their coverage status and the notion of critical target to call targets that are associated with a small number of sensors. The total running time of their heuristic is $0(mn^2)$ where n is the number of sensors, and m the number of targets. Compared to algorithm's results of Slijepcevic and Potkonjak [21], their heuristic produces more cover sets with a slight growth rate in execution time.

In the case of non-disjoint algorithms [26], sensors may participate in more than one cover set. In some cases, this may prolong the lifetime of the network in comparison to the disjoint cover set algorithms, but designing algorithms for non-disjoint cover sets generally induces a higher order of complexity. Moreover, in case of a sensor's failure, non-disjoint scheduling policies are less resilient and less reliable because a sensor may be involved in more than one cover sets. For instance, Cardei et al. [27] present a linear programming (LP) solution and a greedy approach to extend the sensor network lifetime by organizing the sensors into a maximal number of non-disjoint cover sets. Simulation results show that by allowing sensors to participate in multiple sets, the network lifetime increases compared with related work [24]. In [28], the authors have formulated the lifetime problem and suggested another (LP) technique to solve this problem. A centralized solution based on the Garg-Könemann algorithm [29], provably near the optimal solution, is also proposed.

F. Our contribution

There are three main questions, which should be addressed to build a scheduling strategy. We give a brief answer to these three questions to describe our approach before going into details in the subsequent sections.

- **How must the phases for information exchange, decision and sensing be planned over time?** Our algorithm divides the time line into a number of rounds. Each round contains 4 phases: Information Exchange, Leader Election, Decision, and Sensing.
- **What are the rules to decide which node has to be turned on or off?** Our algorithm tends to limit the overcoverage of points of interest to avoid turning on too many sensors covering the same areas at the same time, and tries to prevent undercoverage. The decision is a good compromise between these two conflicting objectives.
- **Which node should make such a decision?** As mentioned in [30], both centralized and distributed algorithms have their own advantages and disadvantages. Centralized coverage algorithms have the advantage of requiring very low processing power from the sensor nodes, which have usually limited processing capabilities. Distributed algorithms are very adaptable to the dynamic and scalable nature of sensors network. Authors in [30] conclude that there is a threshold in terms of network size to switch from a localized to a centralized algorithm. Indeed, the exchange of messages in large networks may consume a considerable amount of energy in a centralized approach compared to a distributed one. Our work does not consider only one leader to compute and to broadcast the scheduling decision to all the sensors. When the network size increases, the network is divided into many subregions and the decision is made by a leader in each subregion.

III. ACTIVITY SCHEDULING

We consider a randomly and uniformly deployed network consisting of static wireless sensors. The wireless sensors are deployed in high density to ensure initially a full coverage of the interested area. We assume that all nodes are homogeneous in terms of communication and processing capabilities and heterogeneous in term of energy provision. The location information is available to the sensor node either through hardware such as embedded GPS or through location discovery algorithms. The area of interest can be divided using the divide-and-conquer strategy into smaller areas called subregions and then our coverage protocol will be implemented in each subregion simultaneously. Our protocol works in rounds fashion as shown in figure 1.

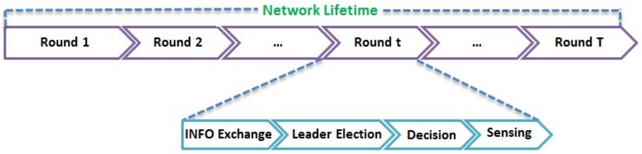

Figure 1: Multi-round coverage protocol

Each round is divided into 4 phases : Information (INFO) Exchange, Leader Election, Decision, and Sensing. For each round there is exactly one set cover responsible for the sensing task. This protocol is more reliable against an unexpected node failure because it works in rounds. On the one hand, if a node failure is detected before making the decision, the node will not participate to this phase, and, on the other hand, if the node failure occurs after the decision, the sensing task of the network will be temporarily affected: only during the period of sensing until a new round starts, since a new set cover will take charge of the sensing task in the next round. The energy consumption and some other constraints can easily be taken into account since the sensors can update and then exchange their information (including their residual energy) at the beginning of each round. However, the pre-sensing phases (INFO Exchange, Leader Election, Decision) are energy consuming for some nodes, even when they do not join the network to monitor the area. Below, we describe each phase in more details.

A. Information exchange phase

Each sensor node j sends its position, remaining energy RE_j, and the number of local neighbours NBR_j to all wireless sensor nodes in its subregion by using an INFO packet and then listens to the packets sent from other nodes. After that, each node will have information about all the sensor nodes in the subregion. In our model, the remaining energy corresponds to the time that a sensor can live in the active mode.

B. Leader election phase

This step includes choosing the Wireless Sensor Node Leader (WSNL), which will be responsible for executing the coverage algorithm. Each subregion in the area of interest will select its own WSNL independently for each round. All the sensor nodes cooperate to select WSNL. The nodes in the same subregion will select the leader based on the received information from all other nodes in the same subregion. The selection criteria in order of priority are: larger number of neighbours, larger remaining energy, and then in case of equality, larger index.

C. Decision phase

The WSNL will solve an integer program (see section IV) to select which sensors will be activated in the following sensing phase to cover the subregion. WSNL will send Active-Sleep packet to each sensor in the subregion based on the algorithm's results.

D. Sensing phase

Active sensors in the round will execute their sensing task to preserve maximal coverage in the region of interest. We will assume that the cost of keeping a node awake (or asleep) for sensing task is the same for all wireless sensor nodes in the network. Each sensor will receive an Active-Sleep packet from WSNL informing it to stay awake or to go to sleep for a time equal to the period of sensing until starting a new round.

We consider a boolean disk coverage model which is the most widely used sensor coverage model in the literature. Each sensor has a constant sensing range R_s. All space points within a disk centered at the sensor with the radius of the sensing range is said to be covered by this sensor. We also assume that the communication range is at least twice the size of the sensing range. In fact, Zhang and Zhou [12] proved that if the transmission range fulfills the previous hypothesis, a complete coverage of a convex area implies connectivity among the working nodes in the active mode.

Instead of working with the coverage area, we consider for each sensor a set of points called primary points. We also assume that the sensing disk defined by a sensor is covered if all the primary points of this sensor are covered. By knowing the position (point center: (p_x, p_y)) of a wireless sensor node and its R_s, we calculate the primary points directly based on the proposed model. We use these primary points (that can be increased or decreased if necessary) as references to ensure that the monitored region of interest is covered by the selected set of sensors, instead of using all the points in the area.

We can calculate the positions of the selected primary points in the circle disk of the sensing range of a wireless sensor node (see figure 2) as follows:

(p_x, p_y) = point center of wireless sensor node
$X_1 = (p_x, p_y)$
$X_2 = (p_x + R_s * (1), p_y + R_s * (0))$
$X_3 = (p_x + R_s * (-1), p_y + R_s * (0))$
$X_4 = (p_x + R_s * (0), p_y + R_s * (1))$
$X_5 = (p_x + R_s * (0), p_y + R_s * (-1))$
$X_6 = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (0))$
$X_7 = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (0))$
$X_8 = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (\frac{-\sqrt{2}}{2}))$
$X_9 = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (\frac{-\sqrt{2}}{2}))$
$X_{10} = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{11} = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{12} = (p_x + R_s * (0), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{13} = (p_x + R_s * (0), p_y + R_s * (\frac{-\sqrt{2}}{2}))$.

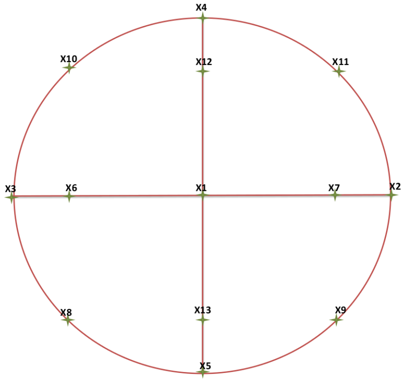

Figure 2: Wireless sensor node represented by 13 primary points

IV. COVERAGE PROBLEM FORMULATION

Our model is based on the model proposed by [31] where the objective is to find a maximum number of disjoint cover sets. To accomplish this goal, authors proposed an integer program, which forces undercoverage and overcoverage of targets to become minimal at the same time. They use binary variables x_{jl} to indicate if sensor j belongs to cover set l. In our model, we consider binary variables X_j, which determine the activation of sensor j in the sensing phase of the round. We also consider primary points as targets. The set of primary points is denoted by P and the set of sensors by J.

For a primary point p, let α_{jp} denote the indicator function of whether the point p is covered, that is:

$$\alpha_{jp} = \begin{cases} 1 & \text{if the primary point } p \text{ is covered} \\ & \text{by sensor node } j, \\ 0 & \text{otherwise.} \end{cases} \qquad (1)$$

The number of active sensors that cover the primary point p is equal to $\sum_{j \in J} \alpha_{jp} * X_j$ where:

$$X_j = \begin{cases} 1 & \text{if sensor } j \text{ is active,} \\ 0 & \text{otherwise.} \end{cases} \qquad (2)$$

We define the Overcoverage variable Θ_p as:

$$\Theta_p = \begin{cases} 0 & \text{if the primary point} \\ & p \text{ is not covered,} \\ \left(\sum_{j \in J} \alpha_{jp} * X_j\right) - 1 & \text{otherwise.} \end{cases} \quad (3)$$

More precisely, Θ_p represents the number of active sensor nodes minus one that cover the primary point p.
The Undercoverage variable U_p of the primary point p is defined by:

$$U_p = \begin{cases} 1 & \text{if the primary point } p \text{ is not covered,} \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

Our coverage optimization problem can then be formulated as follows

$$\begin{cases} \min \sum_{p \in P} (w_\theta \Theta_p + w_U U_p) & \\ \text{subject to :} & \\ \sum_{j \in J} \alpha_{jp} X_j - \Theta_p + U_p = 1, & \forall p \in P \\ \Theta_p \in \mathbb{N}, & \forall p \in P \\ U_p \in \{0, 1\}, & \forall p \in P \\ X_j \in \{0, 1\}, & \forall j \in J \end{cases} \quad (5)$$

- X_j : indicates whether or not the sensor j is actively sensing in the round (1 if yes and 0 if not);
- Θ_p : *overcoverage*, the number of sensors minus one that are covering the primary point p;
- U_p : *undercoverage*, indicates whether or not the primary point p is being covered (1 if not covered and 0 if covered).

The first group of constraints indicates that some primary point p should be covered by at least one sensor and, if it is not always the case, overcoverage and undercoverage variables help balancing the restriction equations by taking positive values. There are two main objectives. First, we limit the overcoverage of primary points in order to activate a minimum number of sensors. Second we prevent the absence of monitoring on some parts of the subregion by minimizing the undercoverage. The weights w_θ and w_U must be properly chosen so as to guarantee that the maximum number of points are covered during each round.

V. SIMULATION RESULTS

In this section, we conducted a series of simulations to evaluate the efficiency and the relevance of our approach, using the discrete event simulator OMNeT++ [6]. We performed simulations for five different densities varying from 50 to 250 nodes. Experimental results were obtained from randomly generated networks in which nodes are deployed over a $(50 \times 25)\ m^2$ sensing field. More precisely, the deployment is controlled at a coarse scale in order to ensure that the deployed nodes can fully cover the sensing field with the given sensing range. 10 simulation runs are performed with different network topologies for each node density. The results presented hereafter are the average of these 10 runs. A simulation ends when all the nodes are dead or the sensor network becomes disconnected (some nodes may not be able to send, to a base station, an event they sense).

Our proposed coverage protocol uses the radio energy dissipation model defined by [13] as energy consumption model for each wireless sensor node when transmitting or receiving packets. The energy of each node in a network is initialized randomly within the range 24-60 joules, and each sensor node will consume 0.2 watts during the sensing period, which will last 60 seconds. Thus, an active node will consume 12 joules during the sensing phase, while a sleeping node will use 0.002 joules. Each sensor node will not participate in the next round if its remaining energy is less than 12 joules. In all experiments, the parameters are set as follows: $R_s = 5\ m$, $w_\Theta = 1$, and $w_U = |P^2|$.

We evaluate the efficiency of our approach by using some performance metrics such as: coverage ratio, number of active nodes ratio, energy saving ratio, energy consumption, network lifetime, execution time, and number of stopped simulation runs. Our approach called strategy 2 (with two leaders) works with two subregions, each one having a size of $(25 \times 25)\ m^2$. Our strategy will be compared with two other approaches. The first one, called strategy 1 (with one leader), works as strategy 2, but considers only one region of $(50 \times 25)\ m^2$ with only one leader. The other approach, called Simple Heuristic, consists in uniformly dividing the region into squares of $(5 \times 5)\ m^2$. During the decision phase, in each square, a sensor is randomly chosen, it will remain turned on for the coming sensing phase.

A. The impact of the number of rounds on the coverage ratio

In this experiment, the coverage ratio measures how much the area of a sensor field is covered. In our case, the coverage ratio is regarded as the number of primary points covered among the set of all primary points within the field. Figure 3 shows the impact of the number of rounds on the average coverage ratio for 150 deployed nodes for the three approaches. It can be seen that the three approaches give similar coverage ratios during the first rounds. From the 9th round the coverage ratio decreases continuously with the simple heuristic, while the two other strategies provide superior coverage to 90% for five more rounds. Coverage ratio decreases when the number of rounds increases due to dead nodes. Although some nodes are dead, thanks to strategy 1 or 2, other nodes are preserved to ensure the coverage. Moreover, when we have a dense sensor network, it leads to maintain the full coverage for a larger number of rounds. Strategy 2 is slightly more efficient than strategy 1, because strategy 2 subdivides the region into 2 subregions and if one of the two subregions becomes disconnected, the coverage may be still ensured in the remaining subregion.

B. The impact of the number of rounds on the active sensors ratio

It is important to have as few active nodes as possible in each round, in order to minimize the communication overhead and maximize the network lifetime. This point is assessed through the Active Sensors Ratio (ASR), which is defined as follows:

$$\text{ASR}(\%) = \frac{\text{Number of active sensors during the current sensing phase}}{\text{Total number of sensors in the network for the region}} \times 100.$$

Figure 4 shows the average active nodes ratio versus rounds for 150 deployed nodes.

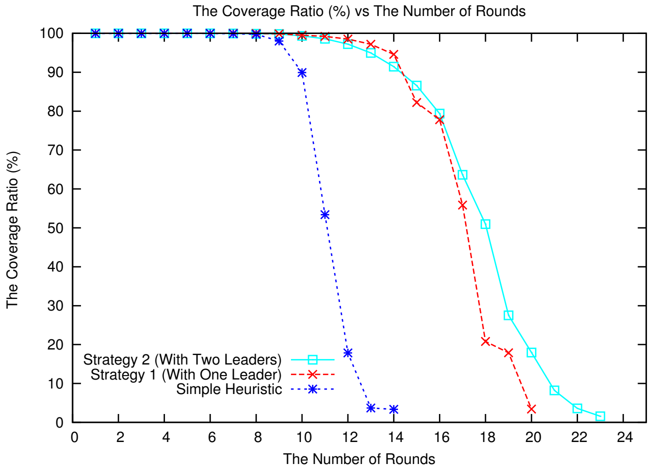

Figure 3: The impact of the number of rounds on the coverage ratio for 150 deployed nodes

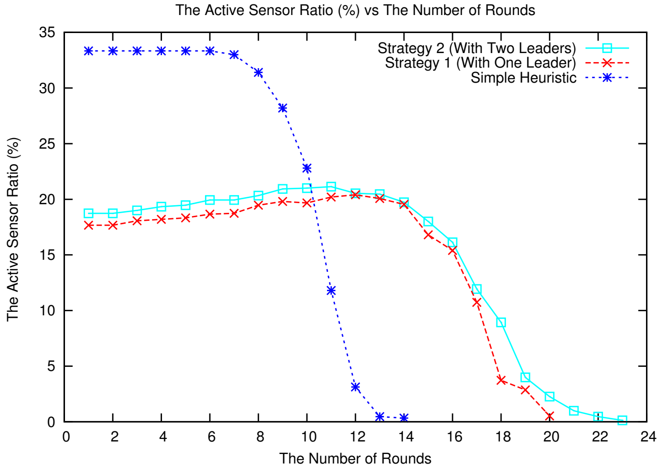

Figure 4: The impact of the number of rounds on the active sensors ratio for 150 deployed nodes

The results presented in figure 4 show the superiority of both proposed strategies, the strategy with two leaders and the one with a single leader, in comparison with the simple heuristic. The strategy with one leader uses less active nodes than the strategy with two leaders until the last rounds, because it uses central control on the whole sensing field. The advantage of the strategy 2 approach is that even if a network is disconnected in one subregion, the other one usually continues the optimization process, and this extends the lifetime of the network.

C. The impact of the number of rounds on the energy saving ratio

In this experiment, we consider a performance metric linked to energy. This metric, called Energy Saving Ratio (ESR), is defined by:

$$\text{ESR}(\%) = \frac{\text{Number of alive sensors during this round}}{\text{Total number of sensors in the network for the region}} \times 100.$$

The longer the ratio is, the more redundant sensor nodes are switched off, and consequently the longer the network may live. Figure 5 shows the average Energy Saving Ratio versus rounds for all three approaches and for 150 deployed nodes.

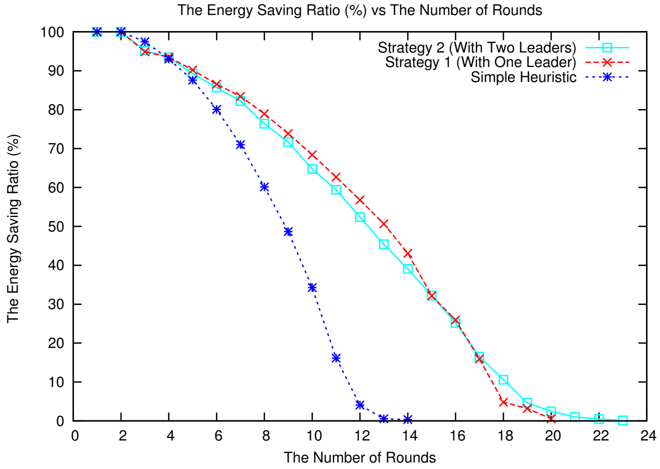

Figure 5: The impact of the number of rounds on the energy saving ratio for 150 deployed nodes

The simulation results show that our strategies allow to efficiently save energy by turning off some sensors during the sensing phase. As expected, the strategy with one leader is usually slightly better than the second strategy, because the global optimization permits to turn off more sensors. Indeed, when there are two subregions more nodes remain awake near the border shared by them. Note that again as the number of rounds increases the two leaders' strategy becomes the most performing one, since it takes longer to have the two subregion networks simultaneously disconnected.

D. The percentage of stopped simulation runs

We will now study the percentage of simulations, which stopped due to network disconnections per round for each of the three approaches. Figure 6 illustrates the percentage of stopped simulation runs per round for 150 deployed nodes. It can be observed that the simple heuristic is the approach, which stops first because the nodes are randomly chosen. Among the two proposed strategies, the centralized one first exhibits network disconnections. Thus, as explained previously, in case of the strategy with several subregions the optimization effectively continues as long as a network in a subregion is still connected. This longer partial coverage optimization participates in extending the network lifetime.

E. The energy consumption

In this experiment, we study the effect of the multi-hop communication protocol on the performance of the strategy with two leaders and compare it with the other two approaches. The average energy consumption resulting from wireless communications is calculated by taking into account the energy spent by all the nodes when transmitting and receiving packets during the network lifetime. This average value, which is obtained for 10 simulation runs, is then divided by the average number of rounds to define a metric allowing a fair comparison between networks having different densities.

Figure 7 illustrates the energy consumption for the different network sizes and the three approaches. The results show that the strategy with two leaders is the most competitive from the

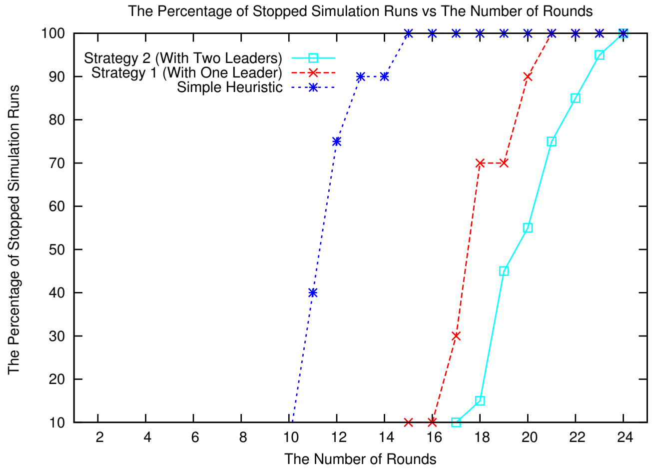

Figure 6: The percentage of stopped simulation runs compared to the number of rounds for 150 deployed nodes

energy consumption point of view. A centralized method, like the strategy with one leader, has a high energy consumption due to many communications. In fact, a distributed method greatly reduces the number of communications thanks to the partitioning of the initial network in several independent subnetworks. Let us notice that even if a centralized method consumes far more energy than the simple heuristic, since the energy cost of communications during a round is a small part of the energy spent in the sensing phase, the communications have a small impact on the network lifetime.

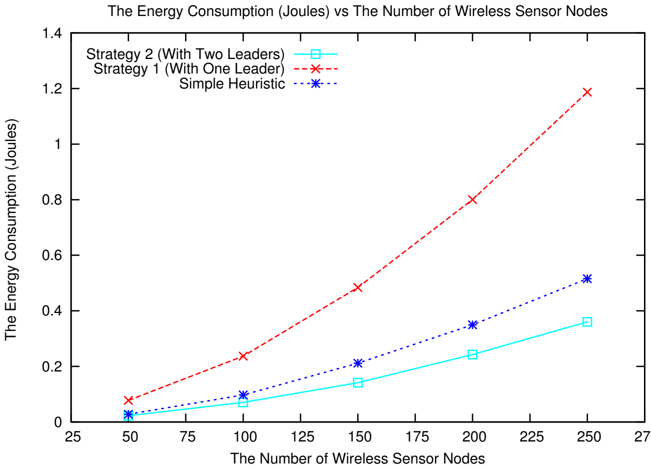

Figure 7: The energy consumption

F. *The impact of the number of sensors on execution time*

A sensor node has limited energy resources and computing power, therefore it is important that the proposed algorithm has the shortest possible execution time. The energy of a sensor node must be mainly used for the sensing phase, not for the pre-sensing ones. Table I gives the average execution times in seconds on a laptop of the decision phase (solving of the optimization problem) during one round. They are given for the different approaches and various numbers of sensors. The lack of any optimization explains why the heuristic has very low execution times. Conversely, the strategy with one leader, which requires to solve an optimization problem considering all the nodes presents redhibitory execution times. Moreover, increasing the network size by 50 nodes multiplies the time by almost a factor of 10. The strategy with two leaders has more suitable times. We think that in distributed fashion the solving of the optimization problem in a subregion can be tackled by sensor nodes. Overall, to be able to deal with very large networks, a distributed method is clearly required.

TABLE I: THE EXECUTION TIME(S) VS THE NUMBER OF SENSORS

Sensors number	Strategy 2 (with two leaders)	Strategy 1 (with one leader)	Simple heuristic
50	0.097	0.189	0.001
100	0.419	1.972	0.0032
150	1.295	13.098	0.0032
200	4.54	169.469	0.0046
250	12.252	1581.163	0.0056

G. *The network lifetime*

Finally, we have defined the network lifetime as the time until all nodes have been drained of their energy or each sensor network monitoring an area has become disconnected. In figure 8, the network lifetime for different network sizes and for both strategy with two leaders and the simple heuristic is illustrated. We do not consider anymore the centralized strategy with one leader, because, as shown above, this strategy results in execution times that quickly become unsuitable for a sensor network.

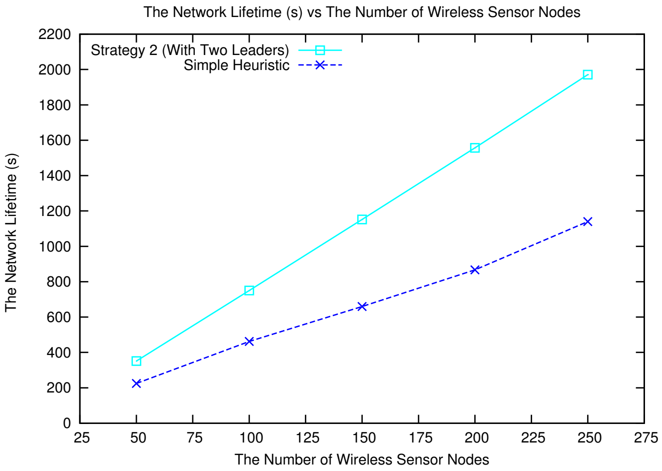

Figure 8: The network lifetime

As highlighted by figure 8, the network lifetime obviously increases when the size of the network increases, with our approach that leads to the larger lifetime improvement. By choosing the best suited nodes, for each round, to cover the region of interest and by letting the other ones sleep in order to be used later in next rounds, our strategy efficiently prolonges the network lifetime. Comparison shows that the larger the sensor number is, the more our strategies outperform the simple heuristic. Strategy 2, which uses two leaders, is the best one because it is robust to network disconnection in one subregion. It also means that distributing the algorithm in each node and subdividing the sensing field into many subregions, which are managed independently and simultaneously, is the most relevant way to maximize the lifetime of a network.

VI. CONCLUSION AND FUTURE WORKS

In this paper, we have addressed the problem of the coverage and the lifetime optimization in wireless sensor networks. This is a key issue as sensor nodes have limited resources in terms of memory, energy and computational power. To cope with this problem, the field of sensing is divided into smaller subregions using the concept of divide-and-conquer method, and then a multi-rounds coverage protocol will optimize coverage and lifetime performances in each subregion. The proposed protocol combines two efficient techniques: network leader election and sensor activity scheduling, where the challenges include how to select the most efficient leader in each subregion and the best representative active nodes that will optimize the network lifetime while taking the responsibility of covering the corresponding subregion. The network lifetime in each subregion is divided into rounds, each round consists of four phases: (i) Information Exchange, (ii) Leader Election, (iii) an optimization-based Decision in order to select the nodes remaining active for the last phase, and (iv) Sensing. The simulations show the relevance of the proposed protocol in terms of lifetime, coverage ratio, active sensors ratio, energy saving, energy consumption, execution time, and the number of stopped simulation runs due to network disconnection. Indeed, when dealing with large and dense wireless sensor networks, a distributed approach like the one we propose allows to reduce the difficulty of a single global optimization problem by partitioning it in many smaller problems, one per subregion, that can be solved more easily.

In future work, we plan to study and propose a coverage protocol, which computes all active sensor schedules in one time, using optimization methods such as swarms optimization or evolutionary algorithms. The round will still consist of 4 phases, but the decision phase will compute the schedules for several sensing phases, which aggregated together, define a kind of meta-sensing phase. The computation of all cover sets in one time is far more difficult, but will reduce the communication overhead.

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