# Distributed Lifetime Coverage Optimization Protocol in 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 Distributed Lifetime Coverage Optimization Protocol (DiLCO) to maintain the coverage and to improve the lifetime in wireless sensor networks is proposed. The area of interest is first divided into subregions using a divide-and-conquer method and then the DiLCO protocol is distributed on the sensor nodes in each subregion. The DiLCO combines two efficient techniques: Leader election for each subregion after that activity scheduling based optimization is planned for each subregion. The proposed DiLCO works into rounds during which a small number of nodes, remaining active for sensing, is selected to ensure coverage so as to maximize the lifetime of wireless sensor network. 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. Compared with some existing protocols, simulation results show that the proposed protocol can prolong the network lifetime and improve the coverage performance effectively.

*Keywords:* Wireless Sensor Networks, Area Coverage, Network lifetime, Optimization, Scheduling.

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## 1. 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]. There are several applications used the WSN including health, home, environmental, military, and industrial applications [2]. One of the major scientific research challenges in WSNs, which are addressed by a large number of literature during the last few years is to design energy efficient approches for coverage and connectivity in WSNs [3]. The coverage problem is one of the fundamental challenges in WSNs [4] that consists in monitoring efficiently and continuously the area of interest. Thelimited 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 [2]. 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. In section 3, the problem definition and some background are described. Section 4 is devoted to the DiLCO Protocol Description. Section 5 gives the coverage model formulation, which is used to schedule the activation of sensors. Section 6 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 7.

## 2. 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 WSNs. Cardei and Wu [7] provide a taxonomy for coverage algorithms in WSNs according to several design choices:

- Sensors scheduling Algorithms, i.e. centralized or distributed/localized algorithms.
- The objective of sensor coverage, i.e. to maximize the network lifetime or to minimize the number of sensors during the sensing period.
- The homogeneous or heterogeneous nature of the nodes, in terms of sensing or communication capabilities.
- The node deployment method, which may be random or deterministic.
- Additional requirements for energy-efficient coverage and connected coverage.

The independency in the cover set (i.e. whether the cover sets are disjoint or non-disjoint) [8] is another design choice that can be added to the above list.

### *2.1. Centralized Approaches*

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 centralized algorithms always provide nearly or close to optimal solution since the algorithm has global view of the whole network. However, its advantage of this type of algorithms is that it requires very low processing power from the sensor nodes, which usually have limited processing capabilities where the schdule of selected sensor nodes will be computed on the base stations and then sent it to the sensor nodes to apply it to monitor the area of interest.

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 [9] 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. Abrams et al. [10] 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 [9] and the generated cover sets do not provide complete coverage of the monitoring zone. [11] 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 [9] but with a larger execution time due to the complexity of the mixed integer programming resolution.

Zorbas et al. [8] presented a centralised greedy algorithm for the efficient production of both node disjoint and non-disjoint cover sets. Compared to algorithm's results of Slijepcevic and Potkonjak [9], their heuristic produces more disjoint cover sets with a slight growth rate in execution time. When producing non-disjoint cover sets, both Static-CCF and Dynamic-CCF provide cover sets offering longer network lifetime than those produced by [12]. Also, they require a smaller number of node participations in order to achieve these results.

In the case of non-disjoint algorithms [13], 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. [12] 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 [11]. In [14], 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 [15], provably near the optimal solution, is also proposed.

### *2.2. Distributed approaches*

In distributed & localized coverage algorithms, the required computation to schedule the activity of sensor nodes will be done by the cooperation among the neighbours nodes. These algorithms may require more computation power for the processing by the cooperated sensor nodes but they are more scaleable for large WSNs. Normally, the localized and distributed algorithms result in non-disjoint set covers.

Some distributed algorithms have been developed in [16, 17, 18, 19, 20, 21] to perform the scheduling so as to coverage preservation. 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 [22], maximum uncovered targets [23]. In [17], 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. [24] 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.

The authors in [21], are developed a distributed adaptive sleep scheduling algorithm (DASSA) for WSNs with partial coverage. DASSA does not require location information of sensors while maintaining connectivity and satisfying a user defined coverage target. In DASSA, nodes use the residual energy levels and feedback from the sink for scheduling the activity of their neighbors. This feedback mechanism reduces the randomness in scheduling that would otherwise occur due to the absence of location information.

In [25], the author proposed a novel distributed heuristic, called Distributed Energy-efficient Scheduling for k-coverage (DESK), which ensures that the energy consumption among the sensors is balanced and the lifetime maximized while the coverage requirement is maintained. This heuristic works in rounds, requires only 1-hop neighbor information, and each sensor decides its status (active or sleep) based on the perimeter coverage model proposed in [26]. Our Work, which is presented in [27] proposed a coverage optimization protocol to improve the lifetime in heterogeneous energy wireless sensor networks. In this work, the coverage protocol distributed in each sensor node in the subregion but the optimization take place over the the whole subregion. We consider only distributing the coverage protocol over two subregions.

The works presented in [28, 29, 30] focuses on a Coverage-Aware, Distributed Energy- Efficient and distributed clustering methods respectively, which aims to extend the network lifetime, while the coverage is ensured. S. Misra et al. [31] proposed a localized algorithm for coverage in sensor networks. The algorithm conserve the energy while ensuring the network coverage by activating the subset of sensors, with the minimum overlap area.The proposed method preserves the network connectivity by formation of the network backbone. More recently, Shibo et al. [32] expressed the coverage problem as a minimum weight submodular set cover problem and proposed a Distributed Truncated Greedy Algorithm (DTGA) to solve it. They take advantage from both temporal and spatial correlations between data sensed by different sensors, and leverage prediction, to improve the lifetime.

In [33], Xu et al. proposed an algorithm, called Geographical Adaptive Fidelity (GAF), which uses geographic location information to divide the area of interest into fixed square grids. Within each grid, it keeps only one node staying awake to take the responsibility of sensing and communication.

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 [18] or regulated [34] over time.

The main contributions of our DiLCO Protocol can be summarized as follows: (1) The high coverage ratio, (2) The reduced number of active nodes, (3) The distributed optimization over the subregions in the area of interest, (4) The distributed dynamic leader election at each round based on some priority factors that led to energy consumption balancing among the nodes in the same subregion, (5) The primary point coverage model to represent each sensor node in the network, (6) The activity scheduling based optimization on the subregion, which are based on the primary point coverage model to activate as less number as possible of sensor nodes to take the mission of the coverage in each subregion, (7) The very low energy consumption, (8) The higher network lifetime.

## 3. Preliminaries

### *3.1. Coverage Problem*

The most discussed coverage problems in literature can be classified into three types [36][37]: area coverage [38](also called full or blanket coverage), target coverage [39], and barrier coverage [40]. 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. The problem of preventing an intruder from entering a region of interest is referred to as the barrier coverage . 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).

### *3.2. Network Lifetime*

Various definitions exist for the lifetime of a sensor network [41]. 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.

### *3.3. Activity Scheduling*

Activity scheduling is to schedule the activation and deac- tivation 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. There are many sensor node scheduling methods are proposed in [42], where they are grouped into two main categories:round-based sensor node scheduling in which, sensor nodes will execute the scheduling algorithm during the initialization of each round and group-based sensor node scheduling in which, each node will performs the scheduling algorithm only once after its deployment and after the execution of scheduling algorithm, all nodes will be allocated into different groups.

## 4. The DiLCO Protocol Description

In this section, we introduce a Distributed Lifetime Coverage Optimization protocol, which is called DiLCO. It is distributed on each subregion in the area of interest. It is based on two efficient techniques: network leader election and sensor activity scheduling for coverage preservation and energy conservation continuously and efficiently to maximize the lifetime in the network. The main features of our DiLCO protocol: i)It divides the area of interest into subregions by using divide-and-conquer concept, ii)It requires only the information of the nodes within the subregion, iii) it divides the network lifetime into rounds, iv)It based on the autonomous distributed decision by the nodes in the subregion to elect the Leader, v)It apply the activity scheduling based optimization on the subregion, vi) it achieves an energy consumption balancing among the nodes in the subregion by selecting different nodes as a leader during the network lifetime, vii) It uses the optimization to select the best representative set of sensors in the subregion by optimize the coverage and the lifetime over the area of interest, viii)It uses our proposed primary point coverage model, which represent the sensing range of the sensor as a set of points, which are used by the our optimization algorithm, ix) It uses a simple energy model that takes communication, sensing and computation energy consumptions into account to evaluate the performance of our Protocol.

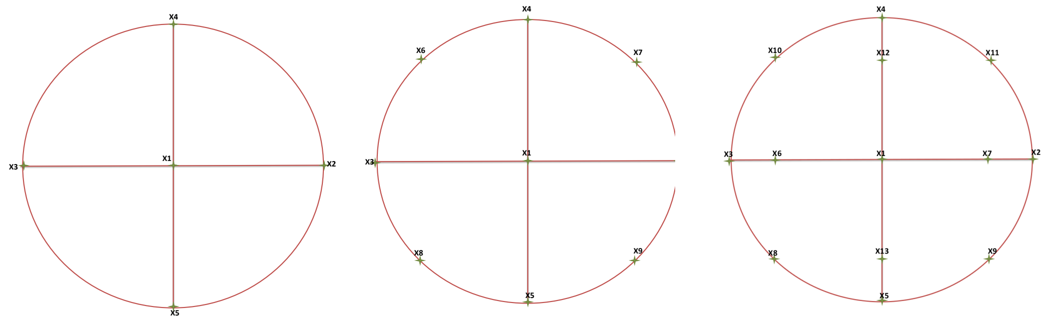
### *4.1. Assumptions and Models*

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 high coverage ratio 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. 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 $R_c \geq 2R_s$. In fact, Zhang and Zhou [19] 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 1) as follows:
$(p_x, p_y)$ = point center of wireless sensor node
$X_1 = (p_x, p_y)$
$X_2 = (p_x + R_s * (1), p_y + R_s * (0))$
$X_3 = (p_x + R_s * (-1), p_y + R_s * (0))$
$X_4 = (p_x + R_s * (0), p_y + R_s * (1))$
$X_5 = (p_x + R_s * (0), p_y + R_s * (-1))$
$X_6 = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (0))$
$X_7 = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (0))$
$X_8 = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (\frac{-\sqrt{2}}{2}))$
$X_9 = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (\frac{-\sqrt{2}}{2}))$
$X_{10} = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{11} = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{12} = (p_x + R_s * (0), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{13} = (p_x + R_s * (0), p_y + R_s * (\frac{-\sqrt{2}}{2}))$.



(a) (b) (c)

Figure 1: Wireless Sensor Node represented by (a)5, (b)9 and (c)13 primary points respectively

### *4.2. The Main Idea*

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 DiLCO protocol works in rounds fashion as shown in figure 2.

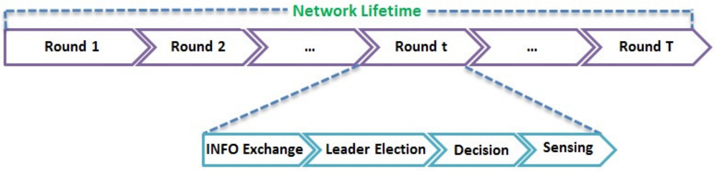


Figure 2: DiLCO protocol

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. We define two types of packets to be used by our DiLCO protocol.

(a) INFO packet: sent by each sensor node to all the nodes of it's subregion for information exchange.
(b) ActiveSleep packet: sent by the leader to all the nodes in the same of it's subregion to inform them to be Active or Sleep during the sensing phase.

There are four status for each sensor node in the network

(a) LISTENING: Sensor has not yet decided.
(b) ACTIVE: Sensor is active.

(c) SLEEP: Sensor decides to turn off.
(d) COMMUNICATION: Sensor is Transmitting or Receiving packet.

Below, we describe each phase in more details.

#### *4.2.1. Information Exchange Phase*

Each sensor node $j$ sends its position, remaining energy $RE_j$, and the number of 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.

#### *4.2.2. 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. The pseudo-code for leader election phase is provided in Algorithm 1.

Where $E_{th}$ is the minimum energy needed to stay active during the sensing phase. As shown in Algorithm 1, the more priority selection factor is the number of $1 - hop$ neighbours, $NBRj$, which can minimize the energy consumption during the communication Significantly.

#### *4.2.3. Decision phase*

The WSNL will solve an integer program (see section 5) 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.

#### *4.2.4. 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

**Algorithm 1:** LEADER ELECTION

```
Input: all the parameters related to information exchange
Output: $node - id$ (: the id of the winner sensor node, which is the leader of current round)
Select the node(s) with higher $NBR_j$ and $RE_j \geqslant E_{th}$ ;
if there are more than two nodes with the same maximum $NBR_j$ then
    if there are more than two nodes with the same maximum $NBR_j$ and the same $RE_j$ then
        Select the node with higher id ;
    else
        Select the node with maximum $RE_j$ ;
else
    Select the node with higher $NBR_j$ ;
return node-id ;
```

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.

### *4.3. DiLCO protocol Algorithm*

we first show the pseudo-code of DiLCO protocol, which is executed by each sensor in the subregion and then describe it in more detail.

The DiLCO protocol work in rounds and executed at each sensor node in the network , each sensor node can still sense data while being in LISTENING mode. Thus, by entering the LISTENING mode at the beginning of each round, sensor nodes still executing sensing task while participating in the leader election and decision phases. More specifically, The DiLCO protocol algorithm works as follow: Initially, the sensor node check it's remaining energy in order to participate in the current round. Each sensor node determines it's position and it's subregion based Embedded GPS or Location Discovery Algorithm. After that, All the sensors collect position coordinates, current remaining energy, sensor node id, and the number of its one-hop live neighbors during the information exchange. It stores this information into a list L. The sensor node enter in listening mode waiting to receive ActiveSleep packet from the leader to take the decision. Each sensor

**Algorithm 2:** DiLCO($s_j$)

```
Initialize the sensor node and determine it's position and it's subregion ;
if $RE_j \geq E_{th}$ then
    Send and Receive INFO Packet to and from other nodes in the subregion;
    Collect information and construct the list L for all nodes in the subregion;
    $s_j$.status = LISTENING;
    if the received INFO Packet = No. of nodes in it's subregion -1 then
        LeaderID ← Algorithm 1;
        if $s_j.ID = LeaderID$ then
            Execute Integer Program Algorithm (Gbest) ;
            for $k \leftarrow 1$ to No. of nodes in subregion do
                if $s_j.ID \neq L_k$ then
                    if $Gbest_k = 1$ then
                        Send ActiveSleep() Packet with status = ACTIVE ;
                    else
                        Send ActiveSleep() Packet with status = SLEEP;
                else
                    if $Gbest_k = 1$ then
                        $s_j$.status = ACTIVE;
                        UPDATE Remaining Energy $RE_j$;
                    else
                        $s_j$.status = SLEEP;
                        UPDATE Remaining Energy $RE_j$;
        else
            Wait ActiveSleep() Packet from the Leader;
            if received ActiveSleep().status = ACTIVE then
                $s_j$.status = ACTIVE;
                UPDATE Remaining Energy $RE_j$;
            else
                $s_j$.status = SLEEP;
                UPDATE Remaining Energy $RE_j$;
else
    Exclude me from entering in the current round
```

node will execute the Algorithm 1 to know who is the leader. After that, if the sensor node is leader, It will execute the integer program algorithm ( see section 5) to optimize the coverage and the lifetime in it's subregion. After the decision, the optimization approach will select the set of sensor nodes to take the mission of coverage during the sensing phase. The leader will send ActiveSleep packet to each sensor node in the subregion to inform him to it's status during the period of sensing, either Active or sleep until the starting of next round. Based on the decision, the leader as other nodes in subregion, either go to be active or go to be sleep during current sensing phase. the other nodes in the same subregion will stay in listening mode waiting the ActiveSleep packet from the leader. After finishing the time period for sensing, all the sensor nodes in the same subregion will start new round by executing the DiLCO protocol and the lifetime in the subregion will continue until all the sensor nodes are died or the network becomes disconnected in the subregion.

## 5. Coverage problem formulation

Our model is based on the model proposed by [43] 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 $\alpha_{jp}$ denote the indicator function of whether the point $p$ is covered, that is:

$$\alpha_{jp} = \left\{ \begin{array}{ll} 1 & \text{if the primary point } p \text{ is covered} \\ & \text{by sensor node } j, \\ 0 & \text{otherwise.} \end{array} \right. \tag{1}$$

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

$$X_j = \left\{ \begin{array}{ll} 1 & \text{if sensor } j \text{ is active,} \\ 0 & \text{otherwise.} \end{array} \right. \tag{2}$$

We define the Overcoverage variable $\Theta_p$ as:

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

More precisely, $\Theta_p$ 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:

$$U_p = \left\{ \begin{array}{ll} 1 & \text{if the primary point } p \text{ is not covered,} \\ 0 & \text{otherwise.} \end{array} \right. \tag{4}$$

Our coverage optimization problem can then be formulated as follows

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

- $X_j$ : indicates whether or not the sensor $j$ is actively sensing in the round (1 if yes and 0 if not);

- $\Theta_p$ : *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 $w_\theta$ and $w_U$ must be properly chosen so as to guarantee that the maximum number of points are covered during each round.

## 6. Simulation Results and Analysis

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]. The simulation parameters are summarized in Table 1

Table 1: Relevant parameters for network initializing.

| Parameter | Value |
|---|---|
| Sensing Field | $(50 \times 25)\ m^2$ |
| Nodes Number | 50, 100, 150, 200 and 250 nodes |
| Initial Energy | 50-75 joules |
| Sensing Period | 20 Minutes |
| $E_{thr}$ | 12.2472 Joules |
| $R_s$ | 5 m |
| $w_{\Theta}$ | 1 |
| $w_U$ | $\|P^2\|$ |

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 a simple energy model defined by [25] that based on [44] with some modification as energy consumption model for each wireless sensor node in the network and for all the simulations.

The modification is to add the energy consumption for receiving the packets as well as we ignore the part that related to the sensing range because we used fixed sensing range. The new energy consumption model will take inro account the energy consumption for communication (packet transmission/reception), data sensing and computational energy.

There are four subsystems in each sensor node that consume energy: the micro-controller unit (MCU) subsystem which is capable of computation, communication subsystem which is responsible for transmitting/receiving messages, sensing subsystem that collects data, and the powe suply which supplies power to the complete sensor node [44]. In our model, we will concentrate on first three main subsystems and each subsystem can be turned on or off depending on the current status of the sensor which is summarized in Table 2.

For the simplicity, we ignore the energy needed to turn on the radio, to start up the sensor node, the transition from mode to another, etc. We also

Table 2: The Energy Consumption Model

| Sensor mode | MCU | Radio | Sensing | Power (mW) |
|---|---|---|---|---|
| Listening | ON | ON | ON | 20.05 |
| Active | ON | OFF | ON | 9.72 |
| Sleep | OFF | OFF | OFF | 0.02 |
| Energy needed to send/receive a 1-bit | | | | 0.2575 |

do not consider the need of collecting sensing data. Thus, when a sensor becomes active (i.e., it already decides it status), it can turn its radio off to save battery. Since our couverage optimization protocol uses two types of the packets, the size of the INFO-Packet and Status-Packet are 112 bits and 16 bits respectively. The value of energy spent to send a message shown in Table 2 is obtained by using the equation in [44] to calculate the energy cost for transmitting messages and we propose the same value for receiving the packets.

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. The energy of each node in a network is initialized randomly within the range 50-75 joules. Each sensor node will not participate in the next round if its remaining energy is less than $E_{thr}$, the minimum energy needed for the node to stay alive during one round.

In the simulations, we introduce the following performance metrics to evaluate the efficiency of our approach:

i) Coverage Ratio (CR): the coverage ratio measures how much the area of a sensor field is covered. In our case, we treated the sensing fields as a grid, and used each grid point as a sample point for calculating the coverage. The coverage ratio can be calculated by:

$$\textsc{cr}(\%) = \frac{n}{N} \times 100.$$

Where: $n$ is the Number of Covered Grid points by the Active Sensors of the all subregions of the network during the current sensing phase and $N$ is total number of grid points in the sensing field of the network. The accuracy of this method depends on the distance between grids. In our simulations, the sensing field has been divided into 50 by 25 grid points, which means there are $51 \times 26 = 1326$ points in total. Therefore, for our simulations, the error in the coverage calculation is less than $1$ %.

ii) Number of Active Sensors Ratio(ASR): 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.The Active Sensors Ratio is defined as follows:

$$\text{ASR}(\%) = \sum_{r=1}^{R} \left( \frac{A_r}{S} \times 100 \right).$$

Where: $A_r$ is the number of active sensors in the subregion $r$ during the current sensing phase, $S$ is the total number of sensors in the network, and $R$ is the total number of the subregions in the network.

iii) Energy Saving Ratio(ESR): is defined by:

$$\text{ESR}(\%) = \sum_{r=1}^{R} \left( \frac{ES_r}{S} \times 100 \right).$$

Where: $ES_r$ is the number of alive sensors in subregion $r$ during this round. The longer the ratio is, the more redundant sensor nodes are switched off, and consequently the longer the network may live.

iv) Energy Consumption:
Energy Consumption (EC) can be seen as the total energy consumed by the sensors during the lifetime of the network divided by the total number of rounds. The EC can be computed as follow:

$$\text{EC} = \frac{\sum\limits_{d=1}^{D} \left( E^{c}_{d} + E^{l}_{d} + E^{a}_{d} + E^{s}_{d} \right)}{D}.$$

Where: D is the total number of rounds. The total energy consumed by the sensors (EC) comes through taking into consideration four main energy factors, which are $E^{c}_{d}$, $E^{l}_{d}$, $E^{a}_{d}$, and $E^{s}_{d}$. The factor $E^{c}_{d}$ represents the 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 round $d$. The $E^{l}_{d}$ represents the energy consumed by all the sensors during the listening mode before taking the decision to go Active or Sleep in round $d$. The $E_d^a$ and $E_d^s$ are refered to enegy consumed by the turned on and turned off sensors in the period of sensing during the round $d$.

v) Network Lifetime: 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.

vi) 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.

vii) The number of stopped simulation runs: we will study the percentage of simulations, which are stopped due to network disconnections per round.

### *6.1. Performance Comparison for differnet subregions*

In this subsection, we will study the performance of our approach for a different number of subregions (Leaders). 10 simulation runs are performed with different network topologies for each node density. The results presented hereafter are the average of these 10 runs. Our approach are called strategy 1 ( With 1 Leader), strategy 2 ( With 2 Leaders), strategy 3 ( With 4 Leaders), and strategy 4 ( With 8 Leaders), strategy 5 ( With 16 Leaders) and strategy 6 ( With 32 Leaders). The strategy 1 ( With 1 Leader) is a centralized approach on all the area of the interest, while strategy 2 ( With 2 Leaders), strategy 3 ( With 4 Leaders), strategy 4 ( With 8 Leaders), strategy 5 ( With 16 Leaders) and strategy 6 ( With 32 Leaders) are distributed on two, four, eight, sixteen, and thirty-two subregions respectively.

#### *6.1.1. The impact of the number of rounds on the coverage ratio*

In this experiment, Figure 3 shows the impact of the number of rounds on the average coverage ratio for 150 deployed nodes for the four strategies.

It can be seen that the six strategies give nearly similar coverage ratios during the first three rounds. As shown in the figure 3, when we increase the number of sub-regions, It will leads to cover the area of interest for a larger number of rounds. Coverage ratio decreases when the number of rounds increases due to dead nodes. Although some nodes are dead, thanks to strategy 5 and strategy 6, 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 5 and strategy 6 are slightly more efficient than other strategies, because they subdivides the area

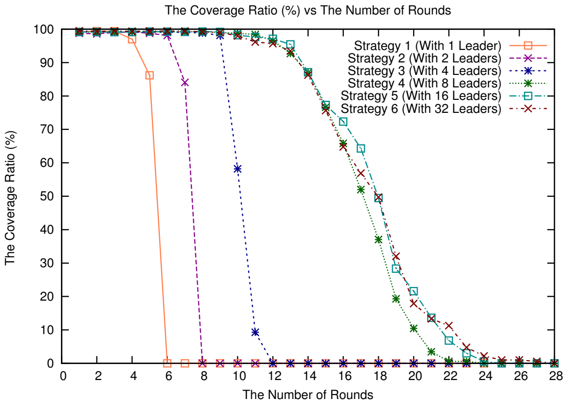


Figure 3: The impact of the number of rounds on the coverage ratio for 150 deployed nodes

of interest into 16 subregions and 32 subregions if one of the subregions becomes disconnected, the coverage may be still ensured in the remaining subregions.

### 6.1.2. *The impact of the number of rounds on the active sensors ratio*

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

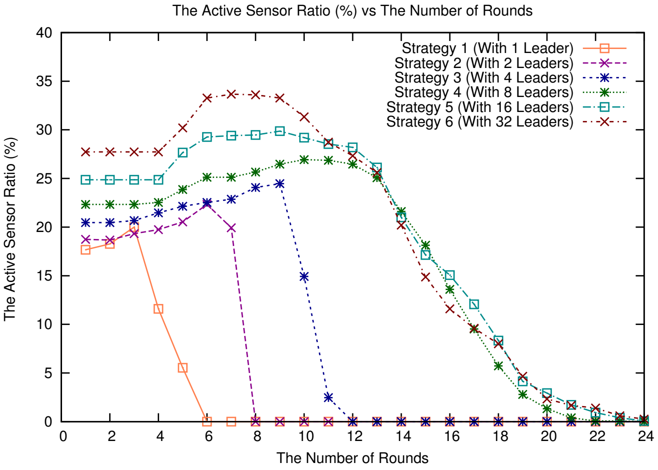


Figure 4: The impact of the number of rounds on the active sensors ratio for 150 deployed nodes

The results presented in figure 4 show the superiority of the proposed strategy 5 and strategy 6, in comparison with the other strategies. The strategy with less number of leaders uses less active nodes than the other strategies, which uses a more number of leaders until the last rounds, because it uses central control on the larger area of the sensing field. The advantage of the strategy 5 and strategy 6 are that even if a network is disconnected in one subregion, the other ones usually continues the optimization process, and this extends the lifetime of the network.

### *6.1.3. The impact of the number of rounds on the energy saving ratio*

In this experiment, we consider a performance metric linked to energy. Figure 5 shows the average energy saving ratio versus number of rounds for all six strategies and for 150 deployed nodes.

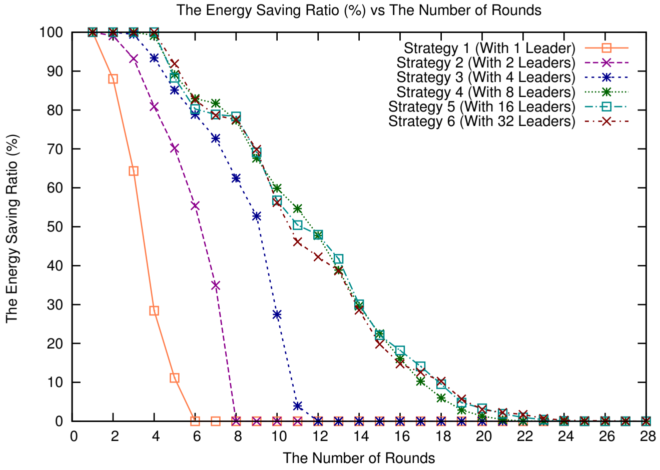


Figure 5: The impact of the number of rounds on the energy saving ratio for 150 deployed nodes

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 5 and strategy 6 are usually slightly better than the other strategies, because the distributed optimization on larger number of subregions permits to minimize the energy needed for communication and It led to save more energy obviously. Indeed, when there are more than one subregion more nodes remain awake near the border shared by them but the energy consumed by these nodes have no effect in comparison with the energy consumed by the communication. Note that again as the number of rounds increases the strategy 5 and strategy 6 becomes the most performing one, since it takes longer to have the Sixteen or Thirty-two subregion networks simultaneously disconnected.

### *6.1.4. The percentage of stopped simulation runs*

Figure 6 illustrates the percentage of stopped simulation runs per round for 150 deployed nodes. It can be observed that the strategy 1 is the approach which stops first because it apply the centralized control on all the area of interest that is why it is first exhibits network disconnections. Thus, as explained previously, in case of the strategy 5 and strategy 6 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.

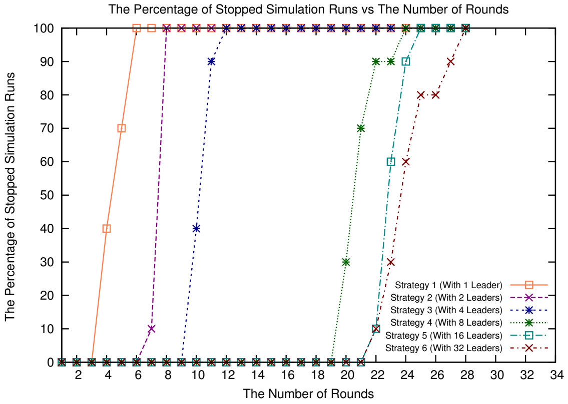


Figure 6: The percentage of stopped simulation runs compared to the number of rounds for 150 deployed nodes

### *6.1.5. The Energy Consumption*

In this experiment, we study the effect of the energy consumed by the sensors during the communication, listening, active, and sleep modes for different network densities. Figure 7 illustrates the energy consumption for the different network sizes and for the four proposed stratgies.

The results show that the strategy with eight leaders is the most competitive from the energy consumption point of view. The other strategies have a high energy consumption due to many communications as well as the energy consumed during the listening before taking the decision. In fact, a distributed method on the subregions greatly reduces the number of commu-

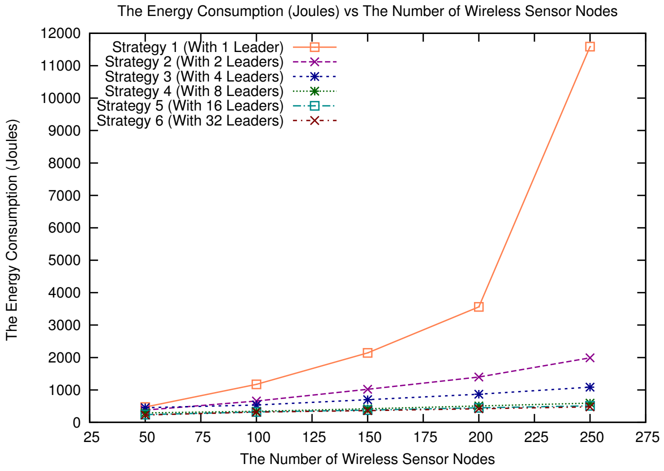


Figure 7: The Energy Consumption

nications and the time of listening so thanks to the partitioning of the initial network in several independent subnetworks.

### *6.1.6. The impact of the number of sensors on execution time*

In this experiment, we study the the impact of the size of the network on the excution time of the our distributed optimization approach. Table 3 gives the average execution times in seconds for the decision phase (solving of the optimization problem) during one round. They are given for the different approaches and various numbers of sensors. We can see from Table 3, that the strategy 6 has very low execution times in comparison with other strategies, because it distributed on larger number of small subregions. Conversely, the strategy 1 which requires to solve an optimization problem considering all the nodes presents high execution times. The strategy 6 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.

### *6.1.7. The Network Lifetime*

Finally, in figure 8, the network lifetime for different network sizes and for the four strategies is illustrated. We see that the strategy 1 results in execution times that quickly become unsuitable for a sensor network as well as the energy consumed during the communication seems to be huge because it used a centralised control on the all the area of interest.

Table 3: The Execution Time(s) vs The Number of Sensors

| Strategy Name | The Number of Sensors | | | | |
|---|---|---|---|---|---|
| | 50 | 100 | 150 | 200 | 250 |
| Strategy 1 | 0.1848 | 1.8957 | 12.2119 | 152.2581 | 1542.5396 |
| Strategy 2 | 0.0466 | 0.2190 | 0.6323 | 2.2853 | 5.6561 |
| Strategy 3 | 0.0118 | 0.0445 | 0.0952 | 0.1849 | 0.3148 |
| Strategy 4 | 0.0041 | 0.0127 | 0.0271 | 0.0484 | 0.0723 |
| Strategy 5 | 0.0025 | 0.0037 | 0.0061 | 0.0083 | 0.0126 |
| Strategy 6 | 0.0008 | 0.0022 | 0.0022 | 0.0032 | 0.0035 |

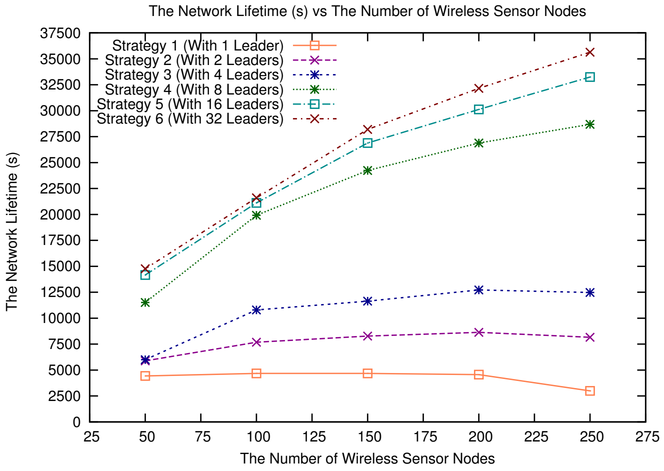


Figure 8: The Network Lifetime

As highlighted by figure 8, the network lifetime obviously increases when the size of the network increases, with our approach strategy 6 that leads to the larger lifetime improvement. By choosing the best suited nodes, for each round, to cover the area of interest and by letting the other ones sleep in order to be used later in next rounds, our strategy 6 efficiently prolonges the network lifetime. Comparison shows that the Strategy 6, which uses 32 leaders, is the best one because it is robust to network disconnection during the network lifetime. It also means that distributing the protocol 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.

### *6.2. Performance Comparison for Different Primary Point Models*

Based on the results, which are conducted in subsection 6.1, we will study the performance of the Strategy 4 approach for a different primary point models. The objective of this comparison is to select the suitable primary point model to be used by our DiLCO protocol. 50 simulation runs are performed with different network topologies for each node density. The results presented hereafter are the average of these 50 runs. In this comparisons, our approaches are called Model 1( With 5 Primary Points), Model 2 ( With 9 Primary Points), Model 3 ( With 13 Primary Points), Model 4 ( With 17 Primary Points), and Model 5 ( With 21 Primary Points). The simulation will applied with strategy 4 by subdividing the area of interest into eight subregions and distribute our strategy 4 approach on the all subregions.

#### *6.2.1. The impact of the number of rounds on the coverage ratio*

In this experiment, we Figure 9 shows the impact of the number of rounds on the average coverage ratio for 150 deployed nodes for the four strategies. It is shown that all models provides a very near coverage ratios during the first twelve rounds, with very small superiority for the models with higher number of primary points. Moreover, when the number of rounds increases, coverage ratio produced by Model 3, Model 4 and Model 5 decreases in comparison with Model 1 and Model 2 due to the high energy consumption during the listening to take the decision after finishing optimization process

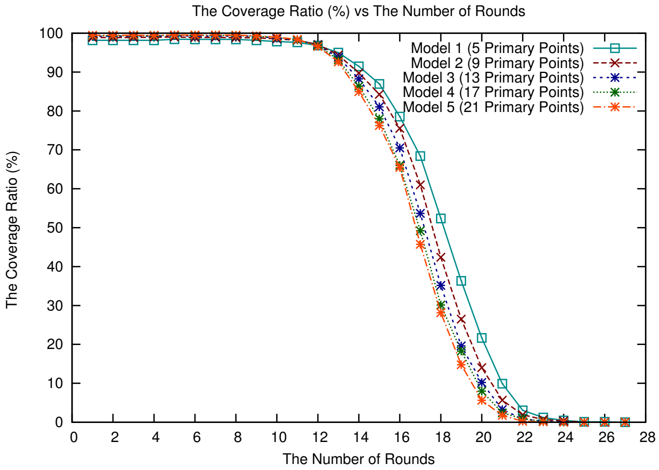


Figure 9: The impact of the number of rounds on the coverage ratio for 150 deployed nodes

for larger number of primary points. As shown in figure 9, Coverage ratio decreases when the number of rounds increases due to dead nodes. Although some nodes are dead, thanks to Model 2, which is slightly more efficient than other Models, because Model 2 balances between the number of rounds and the better coverage ratio in comparison with other Models.

### *6.2.2. The impact of the number of rounds on the active sensors ratio*

Figure 10 shows the average active nodes ratio versus the number of rounds for 150 deployed nodes.

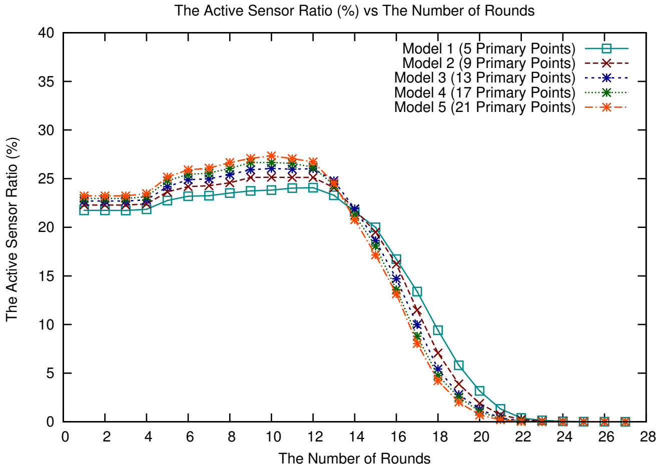


Figure 10: The impact of the number of rounds on the active sensors ratio for 150 deployed nodes

The results presented in figure 10 show the superiority of the proposed Model 1, in comparison with the other Models. The model with less number of primary points uses less active nodes than the other models, which uses a more number of primary points to represent the area of the sensor. According to the results that presented in figure 9, we observe that although the Model 1 continue to a larger number of rounds, but it has less coverage ratio compared with other models.The advantage of the Model 2 approach is to use less number of active nodes for each round compared with Model 3, Model 4 and Model 5, and this led to continue for a larger number of rounds with extending the network lifetime. Model 2 has a better coverage ratio compared to Model 1 and acceptable number of rounds.

### *6.2.3. The impact of the number of rounds on the energy saving ratio*

In this experiment, we study the effect of increasing primary points on the energy conservation in the wireless sensor network. Figure 11 shows the average Energy Saving Ratio versus number of rounds for all four Models and for 150 deployed nodes. The simulation results show that our Models allow to efficiently save energy by turning off the redundant sensors during the sensing phase. As expected, the Model 1 is usually slightly better than the other Models, because it turn on a less number of nodes during the sensing phase in comparison with other models and according to the results, which are observed in figure 9, and It led to save more energy obviously. Indeed, when there are more primary points to represent the area of the sensor leads to activate more nodes to cover them and in the same time ensuring more coverage ratio. From the previous presented results, we see it is preferable to choose the model that balance between the coverage ratio and the number of rounds. The Model 2 becomes the most performing one, since it could apply this requirement where, It can cover the area of interest with a good coverage ratio and for a larger number of rounds prolonging the lifetime of the wireless sensor network.

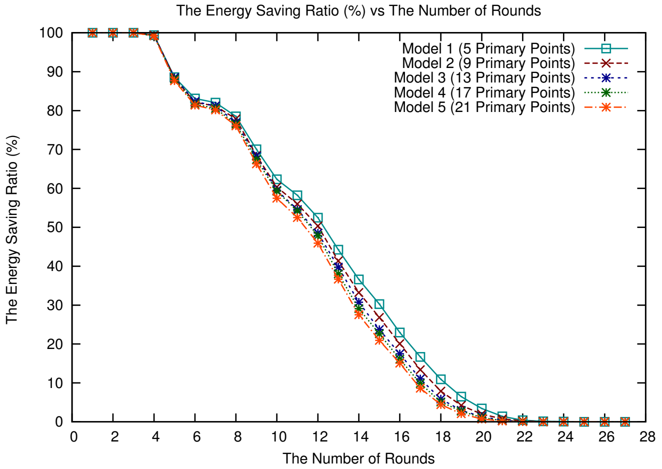


Figure 11: The impact of the number of rounds on the energy saving ratio for 150 deployed nodes

### *6.2.4. The percentage of stopped simulation runs*

In this study, we want to show the effect of increasing the primary points on the number of stopped simulation runs for each round. Figure 12 illustrates the percentage of stopped simulation runs per round for 150 deployed nodes. As shown in Figure 12, when the number of primary points increase leads to increase the percentage of the stopped simulation runs per rounds and starting from round 19 until the the network is died. The reason behind the increase is the increase in the sensors dead when the primary points increases. We can observe that the Model 1 is a better than other models because it conserve more energy by turn on less number of sensors during the sensing phase, but in the same time it preserve the coverage with a less coverage ratio in comparison with other models. Model 2 seems to be more suitable to be used in wireless sensor networks.

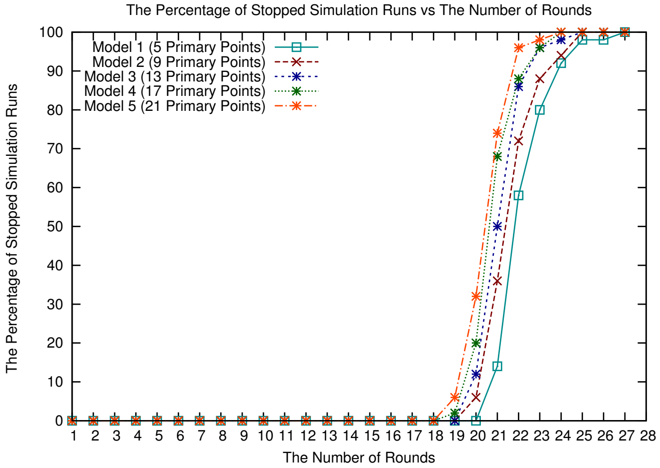


Figure 12: The percentage of stopped simulation runs compared to the number of rounds for 150 deployed nodes

### *6.2.5. The Energy Consumption*

In this experiment, we study the effect of increasing the primary points to represent the area of the sensor on the energy consumed by the wireless sensor network for different network densities. Figure 13 illustrates the energy consumption for the different network sizes and for the five proposed Models.

We see from the results presented in Figure 13, The energy consumed by the network for each round increases when the primary points increases, because the decision for optimization process will takes more time leads to consume more energy during the listening mode. The results show that the Model 1 is the most competitive from the energy consumption point of view

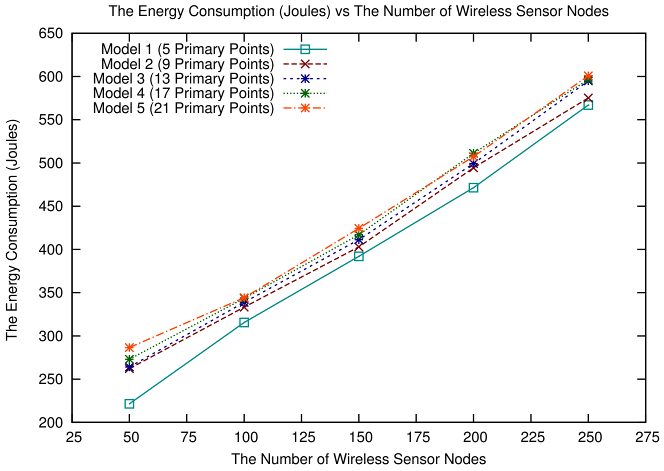


Figure 13: The Energy Consumption

but the worst one from coverage ratio point of view. The other Models have a high energy consumption due to the increase in the primary points, which are led to increase the energy consumption during the listening mode before taking the optimization decision. In fact, we see that the Model 2 is a good candidate to be used the wireless sensor network because I have a good coverage ratio and a suitable energy consumption in comparison with other models.

### *6.2.6. The impact of the number of sensors on execution time*

In this experiment, we study the the impact of the increase in primary points on the excution time of the our distributed optimization approach. Figure 14 gives the average execution times in seconds for the decision phase (solving of the optimization problem) during one round.

They are given for the different primary point models and various numbers of sensors. We can see from Figure 14, that the Model 1 has lower execution time in comparison with other Models, because it used smaller number of primary points to represent the area of the sensor. Conversely, the other primary point models presents higher execution times. Moreover, the Model 2 has more suitable times, coverage ratio, and saving energy ratio leads to continue for a larger number of rounds extending the network lifetime. We think that a good primary point model, this one that balances between the coverage ratio and the number of rounds during the lifetime of the network.

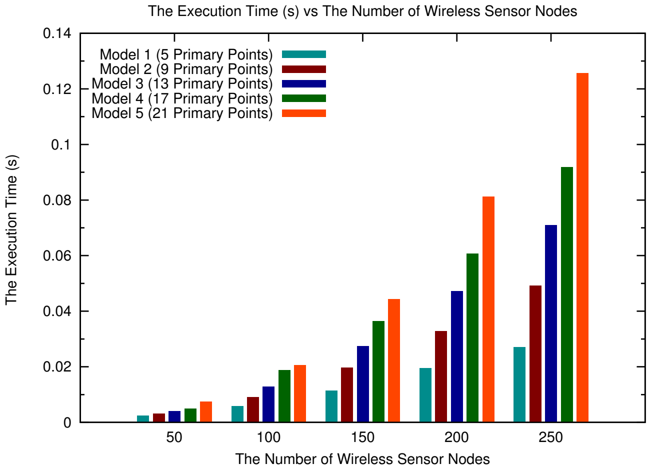


Figure 14: The Execution Time(s) vs The Number of Sensors

### 6.2.7. *The Network Lifetime*

Finally, we will study the effect of increasing the primary points on the lifetime of the network. In figure 15, the network lifetime for different network sizes and for the five proposed models is illustrated. As highlighted by figure 15, the network lifetime obviously increases when the size of the network increases, with our approach Model 1 that leads to the larger lifetime improvement. Comparison shows that the Model 1, which uses less number

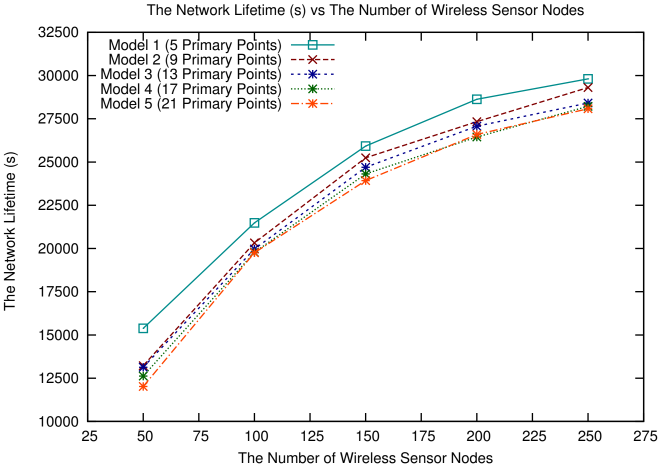


Figure 15: The Network Lifetime

of primary points , is the best one because it is less energy consumption during the network lifetime. It is also the worst one from the point of view of coverage ratio. Our proposed Model 2 efficiently prolongs the network lifetime with a good coverage ratio in comparison with other models.

### *6.3. Performance Comparison for Different Approaches*

Based on the results, which are conducted from previous two subsections, 6.1 and 6.2, we found that Our DiLCO protocol with Strategy 5 and Strategy 6 with Model 2 are the best candidate to be compared with other two approches. The first approach, called DESK that proposed by [25], which is a full distributed coverage algorithm. The second approach, called GAF [33], consists in dividing the region into fixed squares. During the decision phase, in each square, one sensor is chosen to remain on during the sensing phase time. In this subsection, 50 simulation runs are performed with different network topologies. The results presented hereafter are the average of these 50 runs.

#### *6.3.1. The impact of the number of rounds on the coverage ratio*

In this experiment, Figure 16 shows the impact of the number of rounds on the average coverage ratio for 150 deployed nodes for the three approaches.

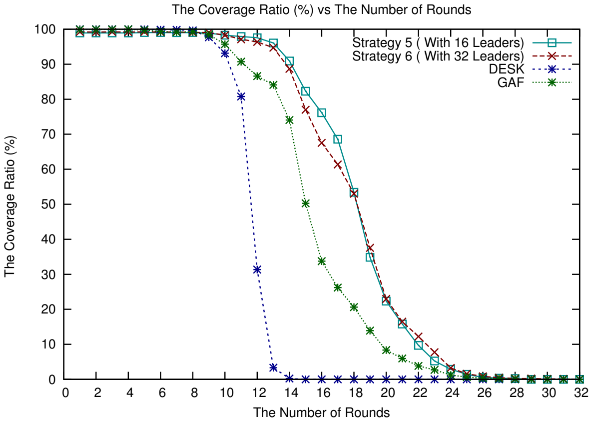


Figure 16: The impact of the number of rounds on the coverage ratio for 150 deployed nodes

It is shown that DESK and GAF provides a a little better coverage ratio with 99.99% and 99.92% against 99.26% and 99.0% produced by our approaches Strategy 5 and Strategy 6 for the lowest number of rounds. This is due to the fact that our DiLCO protocol with Strategy 5 and Strategy 6 put in sleep mode redundant sensors using optimization (which lightly decreases the coverage ratio) while there are more nodes are active in the case of DESK and GAF. Moreover, when the number of rounds increases, coverage ratio produced by DESK and GAF protocols decreases. This is due to dead nodes. However, Our DiLCO protocol with Strategy 5 and Strategy 6 maintains almost full coverage. This is because it optimize the coverage and the lifetime in wireless sensor network by selecting the best representative sensor nodes to take the reponsibilty of coverage during the sensing phase and this will leads to continue for a larger number of rounds and prolonging the network lifetime; although some nodes are dead, sensor activity scheduling of our protocol chooses other nodes to ensure the coverage of the area of interest.

### *6.3.2. 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. Figure 17 shows the average active nodes ratio versus the number of rounds for 150 deployed nodes.

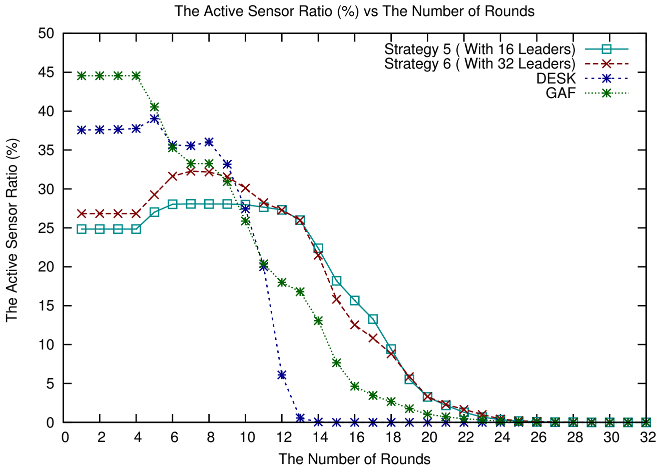


Figure 17: The impact of the number of rounds on the active sensors ratio for 150 deployed nodes

The results presented in figure 17 show the superiority of the proposed DiLCO protocol with Strategy 5 and Strategy 6, in comparison with the other approaches. We can observe that DESK and GAF have 37.5 % and 44.5 % active nodes and our DiLCO protocol with Strategy 5 and Strategy 6 competes perfectly with only 24.8 % and 26.8 % active nodes for the first four rounds. Then as the number of rounds increases our DiLCO protocol with Strategy 5 and Strategy 6 have larger number of active nodes in comparison with DESK and GAF, especially from tenth round because DiLCO gives a better coverage ratio after tenth round than other approaches. We see that the DESK and GAF have less number of active nodes because there are many nodes are died due to the high energy consumption by the redundant nodes during the sensing phase.

*6.3.3. The impact of the number of rounds on the energy saving ratio*

In this experiment, we will perform a comparison study for the performance of our protocol with Strategy 4 with two other approaches from the point of view of energy conservation. Figure 18 shows the average Energy Saving Ratio versus number of rounds for all three approaches and for 150 deployed nodes. The simulation results show that DESK protocol has energy saving ratio 100 % during the first three rounds. After that, the energy saving ratio of DESK decreased obviously during the next rounds due to the died nodes until the died of the network in the $15^{th}$ round.

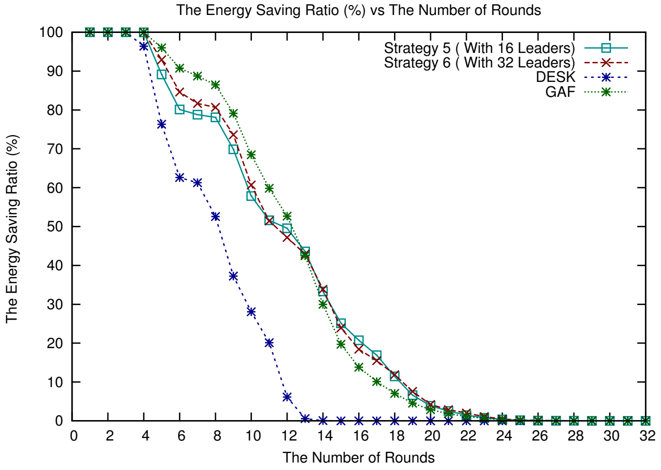


Figure 18: The impact of the number of rounds on the energy saving ratio for 150 deployed nodes

On the other side, our DiLCO protocol with Strategy 5 and Strategy 6 have the same energy saving ratio 100 % during the first four rounds. From the $5^{th}$ round to $12^{th}$ round, GAF provides a beter energy saving ratio because it employs a load balancing for energy usage so that all the nodes remain up and running together as long as possible by selecting the node with higher lifetime in each square and at each round, so it success to prolong the lifetime without taking the coverage ratio into account but it postpond the the increase in the dead nodes until the $13^{th}$ round. After that, our DiLCO protocol with Strategy 5 and Strategy 6 allow to efficiently save energy by turning off the redundant sensors during the sensing phase. As expected, our DiLCO protocol with with Strategy 5 and Strategy 6 is usually slightly better than the other approaches, because the distributed optimization on the subregions permits to minimize the energy needed for communication as well as turn off all the redundant sensor nodes, which are led to save more energy obviously and increase the lifetime of the network. Note that again as the number of rounds increases, our DiLCO protocol becomes the most performing one, since it is distributed the optimization process on the 16 or 32 subregion networks simultaneously so as to optimize the coverage and the lifetime in the network.

### *6.3.4. The percentage of stopped simulation runs*

The results presented in this experiment, is to show the comparison of our DiLCO protocol with Strategy 5 and Strategy 6 with other two approaches from the point of view the stopped simulation runs per round. Figure 19 illustrates the percentage of stopped simulation runs per round for 150 deployed nodes. It can be observed that the DESK is the approach, which stops first because it consumes more energy for communication as well as it turn on a large number of redundant nodes during the sensing phase. Our DiLCO

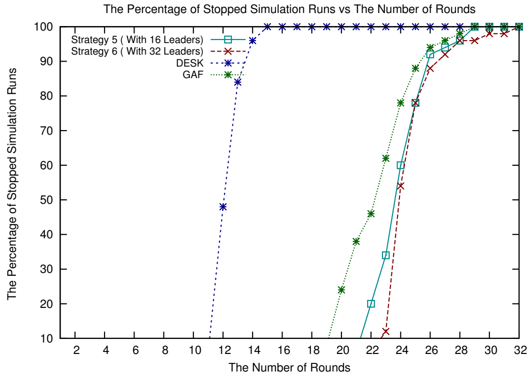


Figure 19: The percentage of stopped simulation runs compared to the number of rounds for 150 deployed nodes

protocol with Strategy 5 and Strategy 6 have less stopped simulation runs in comparison with DESK and GAFbecause it distributed the optimization on several subregions in order to optimize the coverage and the lifetime of the network by activating a less number of nodes during the sensing phase leading to extend the network lifetime and coverage preservation.The optimization effectively continues as long as a network in a subregion is still connected.

### *6.3.5. The Energy Consumption*

In this experiment, we study the effect of the energy consumed by the wireless sensor network during the communication, listening, active, and sleep modes for different network densities and compare it with other approaches. Figure 20 illustrates the energy consumption for the different network sizes and for the four approaches. The results show that our DiLCO protocol with Strategy 5 and Strategy 6 are the most competitive from the energy consumption point of view. The other approaches have a high energy consumption due to activating a larger number of redundant nodes as well as the energy consumed for communication, active and listening modes. In fact, a distributed method on the subregions greatly reduces the number of communications and the time of listening so thanks to the partitioning of the initial network into several independent subnetworks.

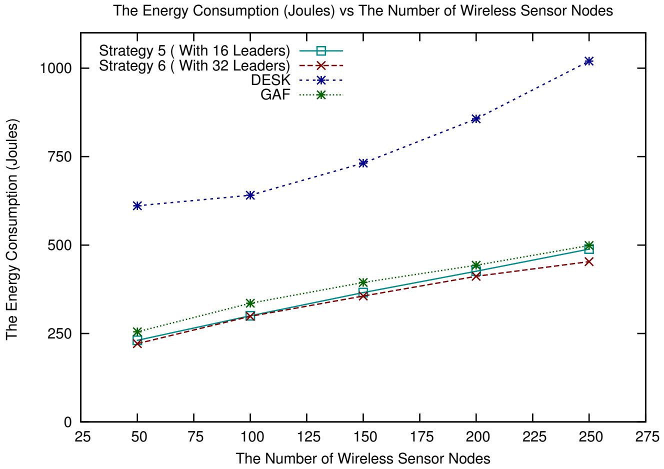


Figure 20: The Energy Consumption

### *6.3.6. The Network Lifetime*

Finally, In this experiment, we will show the superiority of our DiLCO protocol with Strategy 5 and Strategy 6 against other two approaches in prolonging the network lifetime. In Figure 21, the network lifetime for different network sizes and for the four approaches.

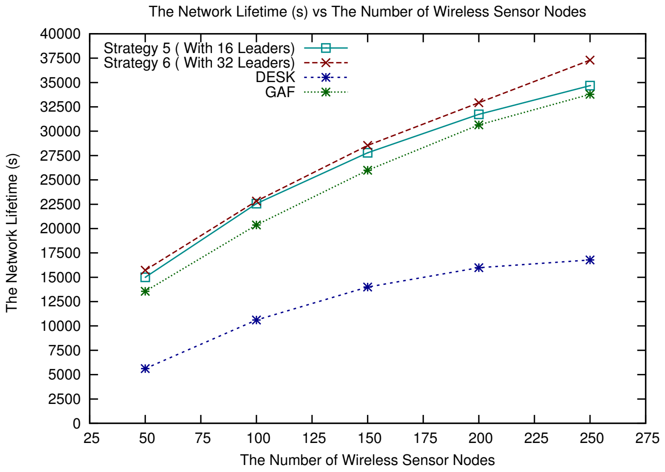


Figure 21: The Network Lifetime

As highlighted by figure 21, the network lifetime obviously increases when the size of the network increases, with our DiLCO protocol with Strategy 5 and Strategy 6 that leads to maximize the lifetime of the network compared with other approaches. By choosing the best suited nodes, for each round, by optimizing the coverage and lifetime of the network to cover the area of interest and by letting the other ones sleep in order to be used later in next rounds, our DiLCO protocol with Strategy 5 and Strategy 6 efficiently prolonges the network lifetime. Comparison shows that our DiLCO protocol with Strategy 5 and Strategy 6, which uses distributed optimization on the subregions, is the best one because it is robust to network disconnection during the network lifetime as well as it consume less energy in comparison with other approaches. 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.

## 7. 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 DiLCO 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 optimization protocol, which computes all active sensor schedules in one time, using optimization methods. 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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