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, followed by an optimization-based planning of activity scheduling decisions 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

In the last years, there has been an increasing development in wireless networking, Micro-Electro-Mechanical Systems (MEMS), and embedded computing technologies, which have led to construct low-cost, small-sized, and low-power sensor nodes that can perform detection, computation, and data communication of surrounding environment. A 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 and cooperate together to monitor the area of interest, so that each measured data can be reported to a monitoring center called sink for further analysis [1].

There are several fields of application covering a wide spectrum for a WSN, including health, home, environmental, military, and industrial applications [2]. One of the major scientific research challenges in WSNs, which has been addressed by a large amount of literature during the last few years, is the design of energy efficient approaches for coverage and connectivity [3]. On the one hand an optimal coverage [4] is required to monitor efficiently and continuously the area of interest and on the other hand the energy consumption must be as low as possible, due to the limited energy of sensors [1] and the impossibility or difficulty to replace and/or recharge their batteries because of the area of interest nature (such as remote, hostile, or unpractical environments) and the cost. So, it is of great relevance for a WSN to be deployed with high density, because spatial redundancy can then be exploited to increase the lifetime of the network. However, turning on all the sensor nodes which monitor the same region at the same time reduces the the lifetime of the network. Therefore, 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].

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

In this section, we summarize the related works regarding coverage lifetime maximization and scheduling, and distinguish our DiLCO protocol from the works presented in the literature. Many centralized algorithms [7, 8, 9, 10, 11, 12, 13] and distributed algorithms [14, 15, 16, 17, 18, 19, 20] for activity scheduling have been proposed in the literature, and based on different assumptions and objectives. In centralized algorithms, a central controller makes all decisions and distributes the results to sensor nodes. In the distributed algorithms, the decision process is localized in each individual sensor node, and only information from neighboring nodes are used for the activity decision.

Zorbas et al. [10] presented a centralised greedy algorithm for the efficient production of both node disjoint and non-disjoint cover sets. The algorithm 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 and they require a smaller number of node participations in order to achieve these results.

Cardei et al. [12] presented 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.

In [21], the authors proposed efficient centralized and distributed truncated greedy to improve the coverage and lifetime in WSNs by exploiting temporal-spatial correlations among sensory data. The basic idea lies in that a sensor node can be turned off safely when its sensory information can be inferred through some prediction methods, like Bayesian inference.

Zhou et al. [22] have presented a centralized and distributed algorithms to conserve energy by exploiting redundancy in the network. In particular, they are addressed the problem of constructing a connected sensor cover in a sensor network model wherein each sensor can adjust its sensing and transmission range. Wang et al. [23] are focused on the energy-efficient coverage optimization problem of WSNs. Based on the models of coverage and energy, stationary nodes are partitioned into clusters by entropy clustering and then a parallel particle swarm optimization is implemented by the cluster heads to maximize the coverage area and minimize the communication energy in each cluster. They are combined the maximum entropy clustering and parallel optimization, in which the stationary and mobile nodes can be organized to achieve energy efficiency of WSNs. In [24], the authors have proposed a monitoring service for sensor networks based on a distributed energy-efficient sensing coverage protocol. Each node is able to dynamically decide it's schedule to guarantee a certain degree of coverage with average energy consumption inversely proportional to the node density.

The works presented in [25, 26, 27] 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. [28] 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. [29] 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 [20], the authors 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 [30]. Our Work, which is presented in [31] 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. In [32], 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.

The work in [33] proposed SALA, a scheduling algorithm based on learning automata, to deal with the problem of dynamic point coverage. In SALA each node in the network is equipped with a set of learning automata. The learning automata residing in each node try to learn the maximum sleep duration for the node in such a way that the detection rate of target points by the node does not degrade dramatically.

In [34], They are addressed the problem of network coverage and connectivity and proposed an efficient solution to maintain coverage, while preserving the connectivity of the network. The proposed solution aims to cover the area of interest, while minimizing the number of the active nodes. The overlap region between two nodes varies according to the distance between them. If the distance between two nodes is maximized, the total coverage area of these nodes will also be maximized. Also, to preserve the connectivity of the network, each node should be in the communication range of at least one other node.

Rizvi et al. [35] have investigated the problem of constructing a Connected Dominating Set (CDS) , which provides better sensing coverage in an energy efficient manner. The have presented a CDS based topology control algorithm, A1, which forms an energy efficient virtual backbone. They are proven that a single phase topology construction with fewer number of messages lead towards an efficient algorithm.

In [36], the authors are defined a maximum sensing coverage region (MSCR) problem and presented a novel gossip-based sensing-coverage-aware algorithm to solve the problem. In this approach, nodes gossip with their neighbors about their sensing coverage region where nodes decide locally to be an active or a sleeping node. In this method, the redundant node can reduce its activities whenever its sensing region is covered by enough neighbors.

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, (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 energy consumption model (8) The very low energy consumption, (9) The higher network lifetime.

3. Preliminaries:

There are some design issues, which should be taken into consideration for coverage problem such as: coverage type, deployment method, coverage degree, coverage ratio, activity scheduling, network connectivity and network lifetime [38].

3.1. Coverage Problem

Coverage reflects how well a sensor field is monitored, is one of the most important performance metrics to measure WSNs. The most discussed coverage problems in literature can be classified into three types [37][38]: area coverage [39](also called full or blanket coverage), target coverage [40], and barrier coverage [41]. 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. Deployment Method

Deployment reflects how a sensor network is constructed over the sensing field. There are two ways to deploy the sensor nodes over the sensing field, fixed and random. The fixed sensor placement could be used in small sensing field while for a large sensor network, remote and hostile environment might the random sensor placement is recommended. The deployment of wireless sensor network could be dense or sparse. A dense deployment has a larger number of sensor nodes over the area of interest while sparse deployment has lower number of sensor nodes over the sensing field. The dense deployment method is used in situations where it is very important for every event to be detected or when it is important to have multiple sensors cover an area. Sparse deployment might be used when the cost of the sensors make a dense deployment is very expensive or to achieve maximum coverage using the minimum number of sensor nodes.

3.3. Coverage Degree

Coverage degree refers to the number of sensor nodes, which cover point in the sensing disk model. As the number of sensor nodes, which cover a point increase, the robustness of coverage increases. Coverage degree is represented one of the QoS requirements in WSNs.

3.4. Coverage Ratio

Coverage ratio refers to how much area of the total area of interest or how many points of the total points in the sensing field, which satisfy the QoS requirement of coverage degree. Coverage ratio can be seen as one of the QoS requirement in WSNs.

3.5. 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 [43], 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.

3.6. Network Connectivity

Network connectivity refers to ensure that the WSN connected with the sink. The connected WSN should be guarantee that every sensor node in WSN can send the sensed data to other sensor nodes and to the sink using multihop communication. So, by using the sensing disk coverage model, each sensor node can communicate with each other using the communication range of the sensor node.

3.7. Network Lifetime

Various definitions exist for the lifetime of a sensor network [42]. 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.

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.

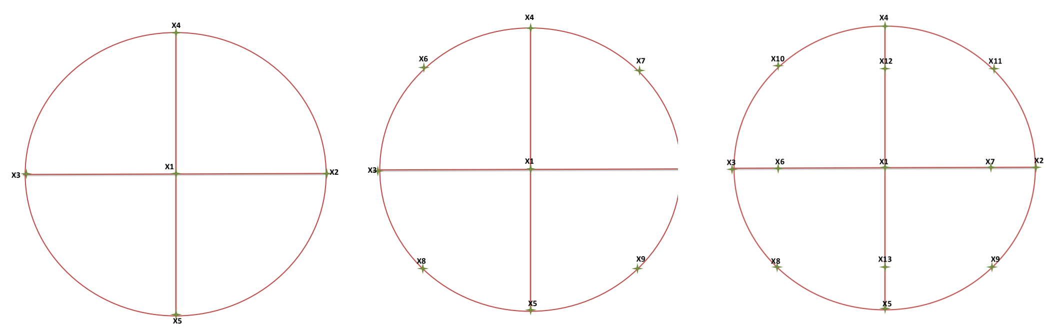
4.1. Assumptions and Models

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 [17] 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.

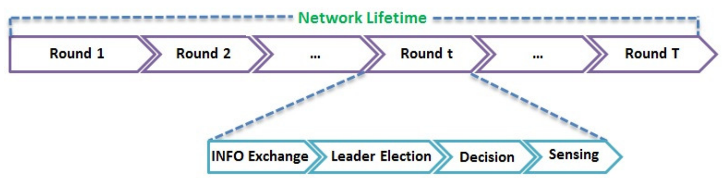


Figure 2: DiLCO protocol

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 is waiting for a decision (to be active or not)
(b) COMPUTATION: Sensor applies the optimization process as leader

(c) ACTIVE: Sensor is active
(d) SLEEP: Sensor is turned off
(e) 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

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 ;

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.

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

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 $\leftarrow$ **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 receive ActiveSleep packet from the leader to take the decision. Each sensor 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 [44] 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:

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

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 Θ_p as:

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

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:

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

Our coverage optimization problem can then be formulated as follows

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

- 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.

6. Simulation Results and Analysis

6.1. Simulation framework, energy consumption model and performance metrics

In this subsection, we conducted a series of simulations to evaluate the efficiency and the relevance of our protocol DiLCO, 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	(50×25) m^2
Nodes Number	50, 100, 150, 200 and 250 nodes
Initial Energy	500-700 joules
Sensing Period	60 Minutes
E_{thr}	36 Joules
R_s	5 m
w_{Θ}	1
w_U	$\|P^2\|$

25 simulation runs are performed with different network topologies. The results presented hereafter are the average of these 25 runs. We performed simulations for five different densities varying from 50 to 250 nodes. Experimental results are obtained from randomly generated networks in which nodes are deployed over a (50×25) m^2 sensing field. More precisely, the deployment is controlled at a coarse scale in order to ensure that the deployed nodes can cover the sensing field with the given sensing range.

Our DiLCO protocol is declined into five versions: DiLCO-2, DiLCO-4, DiLCO-8, DiLCO-16, and DiLCO-32, corresponding to 2, 4, 8, 16 or 32 subregions (leaders).

We use an energy consumption model proposed by [20] and based on [45] with slight modifications. The energy consumption for sending/receiving the packets is added whereas the part related to the sensing range is removed because we consider a fixed sensing range.

For our energy consumption model, we refer to the sensor node (Medusa II) which uses Atmels AVR ATmega103L microcontroller [45]. The typical architecture of a sensor is composed of four subsystems : the MCU subsystem which is capable of computation, communication subsystem (radio) which is responsible for transmitting/receiving messages, sensing subsystem that collects data, and the power supply which powers the complete sensor node [45]. Each of the first three subsystems can be turned on or off depending on the current status of the sensor. Energy consumption (expressed in milliWatt per second) for the different status of the sensor is summarized in Table 2. The energy needed to send or receive a 1-bit is equal to $0.2575mW$.

Table 2: The Energy Consumption Model

Sensor mode	MCU	Radio	Sensing	Power (mWs)
Listening	ON	ON	ON	20.05
Active	ON	OFF	ON	9.72
Sleep	OFF	OFF	OFF	0.02
Computation	ON	ON	ON	26.83

For sake of simplicity we ignore the energy needed to turn on the radio, to start up the sensor node, the transition from mode to another, etc. Thus, when a sensor becomes active (i.e., it already decides it's status), it can turn its radio off to save battery. DiLCO protocol uses two types of packets for communication. The size of the INFO-Packet and Status-Packet are 112 bits and 24 bits respectively. The value of energy spent to send a 1-bit-content message is obtained by using the equation in [45] to calculate the energy cost for transmitting messages and we propose the same value for receiving the packets.

The initial energy of each node is randomly set in the interval $[500 - 700]$. Each sensor node will not participate in the next round if its remaining energy is less than $E_{th} = 36 Joules$, the minimum energy needed for the node to stay alive during one round. This value has been computed by multiplying the energy consumed in active state (9.72 mWs) by the time in second for one round (3600 seconds). According to the interval of initial energy, a sensor may be alive during at most 20 rounds.

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:

$$\text{CR}(\%) = \frac{n^t}{N} \times 100.$$

Where: n^t is the number of covered grid points by the active sensors of all subregions during round t in the current sensing phase and N is total number of grid points in the sensing field of the network.

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:

$$\text{ASR}(\%) = \frac{\sum\limits_{r=1}^{R} A_r^t}{S} \times 100.$$

Where: A_r^t is the number of active sensors in the subregion r during round t in 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) **Network Lifetime**: we define the network lifetime as the time until the coverage ratio drops below a predefined threshold. We denoted by $Lifetime95$ (respectively $Lifetime50$) as the amount of time during which the network can satisfy an area coverage greater than 95% (repectively 50%). We assume that the network is alive until all nodes have been drained of their energy or the sensor network becomes disconnected . 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.

iv) **Energy Consumption**:
Energy Consumption (EC) can be seen as the total energy consumed by the sensors during the $Lifetime95$ or $Lifetime50$ divided by the number of rounds. The EC can be computed as follow:

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

Where: D is the number of rounds during $Lifetime95$ or $Lifetime50$. 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, E^s_d and E^p_d. The energy consumption E^c_d for wireless communications is calculated by taking into account the energy spent by all the nodes while 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. E^a_d and E^s_d refer to energy consumed in the active mode or in the sleeping mode. The E^p_d refers to energy consumed by the computation (processing) to solve the integer program.

v) **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.

vi) **Stopped simulation runs**: A simulation ends when the sensor network becomes disconnected (some nodes are dead and are not able to send information to the base station). We report the number of simulations that are stopped due to network disconnections and for which round it occurs.

6.2. Performance Comparison for differnet subregions

In this subsection, we are studied the performance of our DiLCO protocol for a different number of subregions (Leaders). The DiLCO-1 protocol is a centralized approach on all the area of the interest, while DiLCO-2, DiLCO-4, DiLCO-8, DiLCO-16 and DiLCO-32 are distributed on two, four, eight, sixteen, and thirty-two subregions respectively. We did not take the DiLCO-1 protocol in our simulation results because it need high execution time to give the decision leading to consume all it's energy before producing the solution for optimization problem.

6.2.1. Coverage Ratio

In this experiment, Figure 3 shows the average coverage ratio for 150 deployed nodes.

It can be seen that the DiLCO protocol (with 4, 8, 16 and 32 subregions) gives nearly similar coverage ratios during the first thirty rounds. DiLCO-2 protocol gives near similar coverage ratio with other ones for first 10 rounds and then decreased until the died of the network in the round 18^{th} because it consume more energy with the effect of the network disconnection. As shown in the figure 3, as the number of subregions increases , the coverage

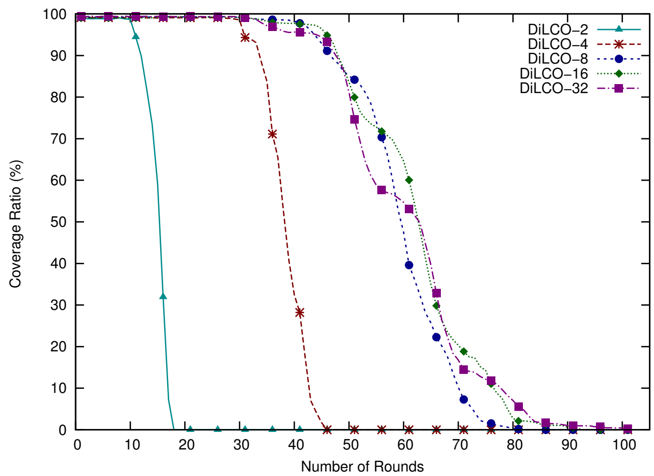


Figure 3: The impact of the number of rounds on the coverage ratio for 150 deployed nodes

preservation for area of interest increases 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 DiLCO-8, DiLCO-16 and DiLCO-32 protocols, other nodes are preserved to ensure the coverage. Moreover, when we have a dense sensor network, it leads to maintain the coverage for a larger number of rounds. DiLCO-8, DiLCO-16 and DiLCO-32 protocols are slightly more efficient than other protocols, because they subdivides the area of interest into 8, 16 and 32 subregions if one of the subregions becomes disconnected, the coverage may be still ensured in the remaining subregions.

6.2.2. Active Sensors Ratio

Figure 4 shows the average active nodes ratio for 150 deployed nodes. The results presented in figure 4 show the increase in the number of subregions led to increase in the number of active nodes. The DiLCO-16 and DiLCO-32 protocols have a larger number of active nodes but it preserve the coverage for a larger number of rounds. The advantage of the DiLCO-16, and DiLCO-32 protocols 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.

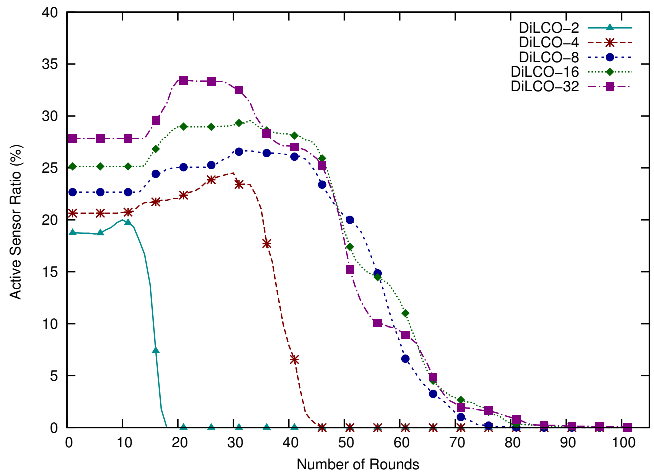


Figure 4: The impact of the number of rounds on the active sensors ratio for 150 deployed nodes

6.2.3. The percentage of stopped simulation runs

Figure 5 illustrates the percentage of stopped simulation runs per round for 150 deployed nodes.

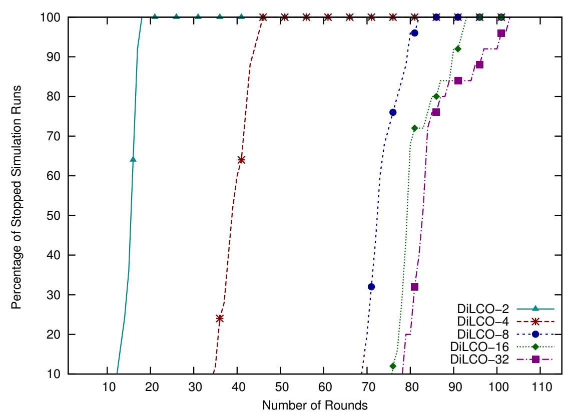


Figure 5: The percentage of stopped simulation runs compared to the number of rounds for 150 deployed nodes

It can be observed that the DiLCO-2 is the approach which stops first because it applied the optimization on only two subregions for the area of interest that is why it is first exhibits network disconnections. Thus, as explained previously, in case of the DiLCO-16 and DiLCO-32 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.

6.2.4. The Energy Consumption

We measure the energy consumed by the sensors during the communication, listening, computation, active, and sleep modes for different network densities and compare it for different subregions. Figures 6 and 7 illustrate the energy consumption for different network sizes for $Lifetime95$ and $Lifetime50$.

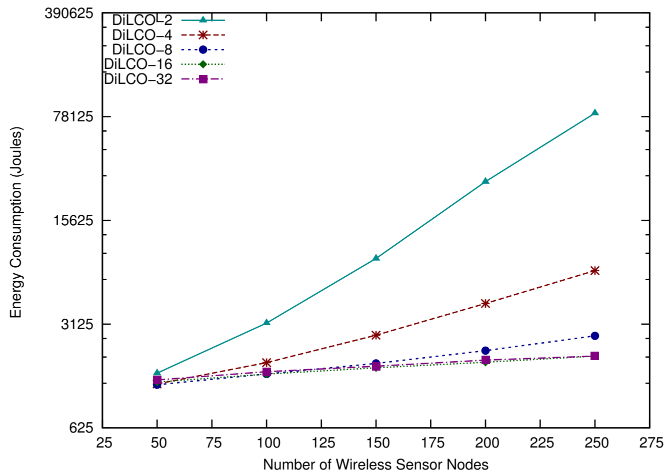


Figure 6: The Energy Consumption for Lifetime95

The results show that DiLCO-16 and DiLCO-32 are the most competitive from the energy consumption point of view but as the network size increase the energy consumption increase compared with DiLCO-2, DiLCO-4 and DiLCO-8. The other approaches have a high energy consumption due to the energy consumed during the different modes of the sensor node.

As shown in Figures 6 and 7 , DiLCO-2 consumes more energy than the other versions of DiLCO, especially for large sizes of network. This is easy to understand since the bigger the number of sensors involved in the integer program, the larger the time computation to solve the optimization problem as well as the higher energy consumed during the communication. In fact, a distributed method on the subregions greatly reduces the number

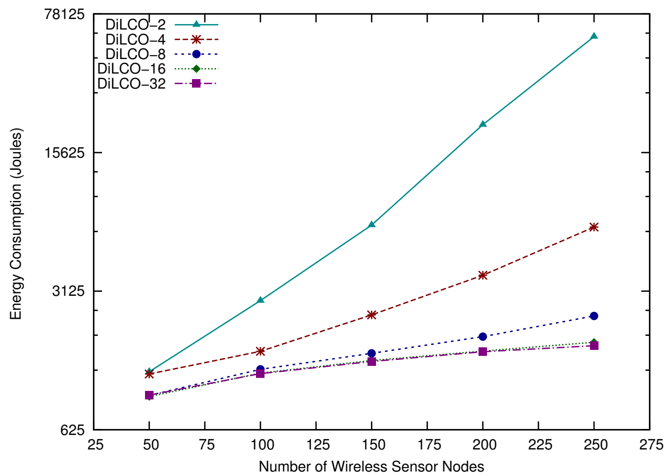


Figure 7: The Energy Consumption for Lifetime50

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

6.2.5. 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. Figure 8 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. The original execution time is computed on a laptop DELL with intel Core i3 2370 M (2.4 GHz) processor (2 cores) and the MIPS (Million Instructions Per Second) rate equal to 35330. To be consistent with the use of a sensor node with Atmels AVR ATmega103L microcontroller (6 MHz) and a MIPS rate equal to 6 to run the optimization resolution, this time is multiplied by 2944.2 $\left(\frac{35330}{2} \times 6\right)$ and reported on Figure 8 for different network sizes.

We can see from figure 8, that the DiLCO-32 has very low execution times in comparison with other DiLCO versions, because it distributed on larger number of small subregions. Conversely, the DiLCO-2 which requires to solve an optimization problem considering half the nodes in each subregion presents high execution times.

The DiLCO-32 has more suitable times in the same time it turn on redundent nodes more. We think that in distributed fashion the solving of the optimization problem in a subregion can be tackled by sensor nodes. Overall,

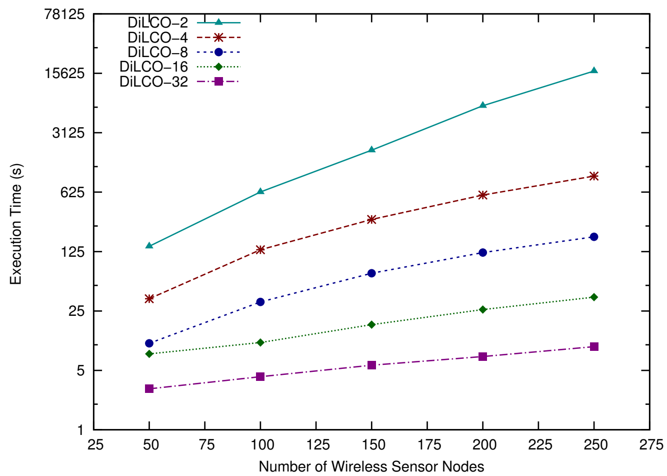


Figure 8: Execution Time (in seconds)

to be able to deal with very large networks, a distributed method is clearly required.

6.2.6. The Network Lifetime

In figure 9 and 10, network lifetime, $Lifetime95$ and $Lifetime50$ respectively, are illustrated for different network sizes.

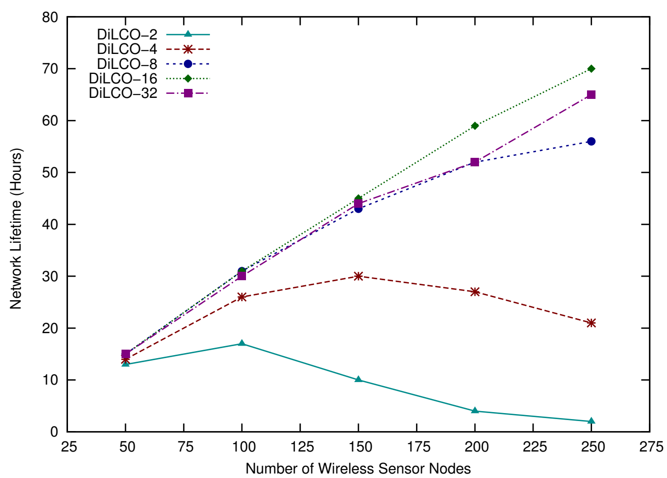


Figure 9: The Network Lifetime for $Lifetime95$

We see that the DiLCO-2 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 is distributed over only two subregions.

As highlighted by figures 9 and 10, the network lifetime obviously increases when the size of the network increases, with our DiLCO-16 protocol 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 DiLCO-16 protocol efficiently extends the network lifetime because the benefit from the optimization with 16 subregions is better than the DiLCO-32 with 32 subregion. DilCO-32 protocol puts in active mode a larger number of sensor nodes especially near the bordes of the subdivisions.

Comparison shows that the DiLCO-16 protocol, which uses 16 leaders, is the best one because it is used less number of active nodes during the network lifetime compared with DiLCO-32. 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.

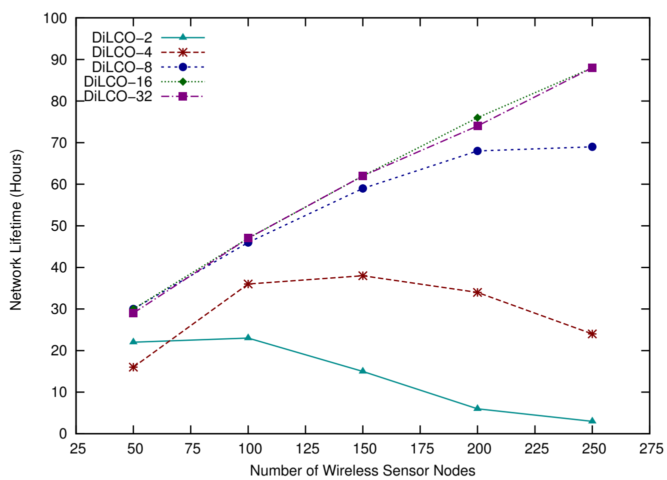


Figure 10: The Network Lifetime for $Lifetime50$

6.3. Performance Study for Primary Point Models

In this subsection, we are studied the performance of the DiLCO 16 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.

In this comparisons, our DiLCO-16 protocol are used with five models which 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).

6.3.1. Coverage Ratio

In this experiment, we Figure 11 shows the average coverage ratio for 150 deployed nodes. It is shown that all models provides a very near coverage

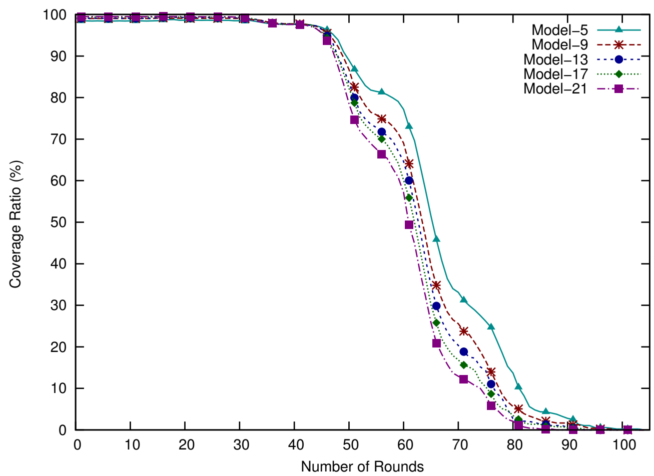


Figure 11: The impact of the number of rounds on the coverage ratio for 150 deployed nodes

ratios during the network lifetime, 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 for larger number of primary points. As shown in figure 11, 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 it is balanced between the number of rounds and the better coverage ratio in comparison with other Models.

6.3.2. Active Sensors Ratio

Figure 12 shows the average active nodes ratio for 150 deployed nodes.

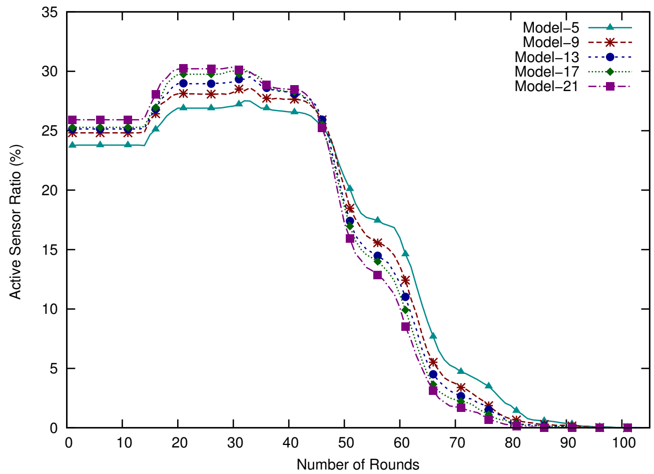


Figure 12: The impact of the number of rounds on the active sensors ratio for 150 deployed nodes

The results presented in figure 12 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 11, 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.

6.3.3. 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 13 illustrates the percentage of stopped simulation runs per round for 150 deployed nodes.

As shown in Figure 13, when the number of primary points are increased, the percentage of the stopped simulation runs per rounds is increased. The reason behind the increase is the increase in the sensors dead when the primary points increases. We are observed that the Model 1 is a better than other models because it conserve more energy by turn on less number of sen-

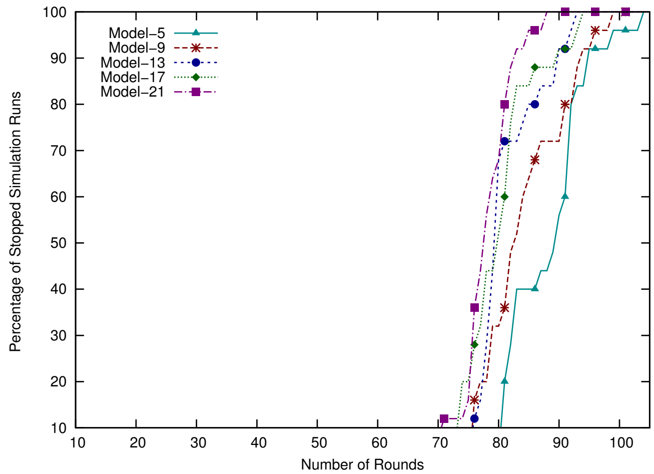


Figure 13: The percentage of stopped simulation runs compared to the number of rounds for 150 deployed nodes

sors 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.

6.3.4. 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. Figures 14 and 15 illustrate the energy consumption for different network sizes for $Lifetime95$ and $Lifetime50$.

We see from the results presented in Figures 14 and 15, 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 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 producing the solution by solving the optimization process. In fact, we see that the Model 2 is a good candidate to be used by wireless sensor network because It preserve a good coverage ratio and a suitable energy consumption in comparison with other models.

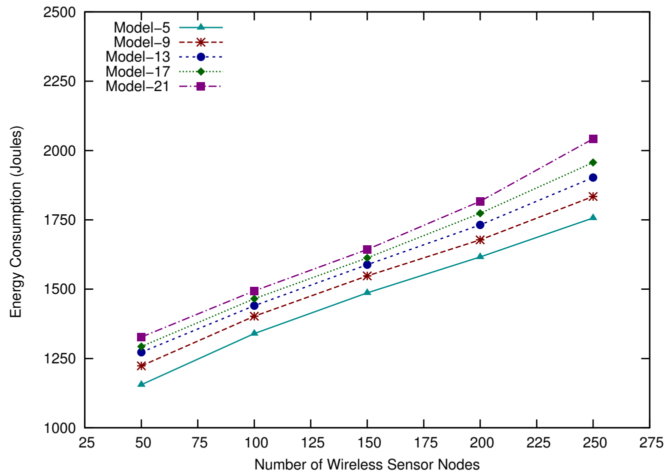


Figure 14: The Energy Consumption with $95\% - Lifetime$

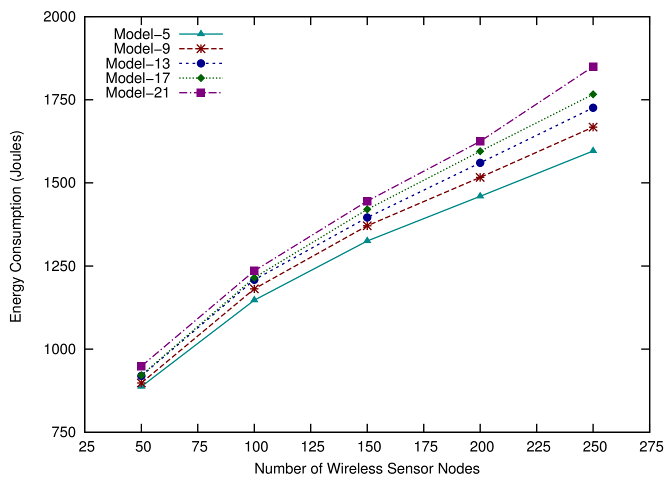


Figure 15: The Energy Consumption with $Lifetime50$

6.3.5. Execution Time

In this experiment, we study the impact of the increase in primary points on the excution time of our DiLCO protocol. Figure 16 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 16, that the Model 1 has lower execution time in comparison with other Models, because it used smaller number of

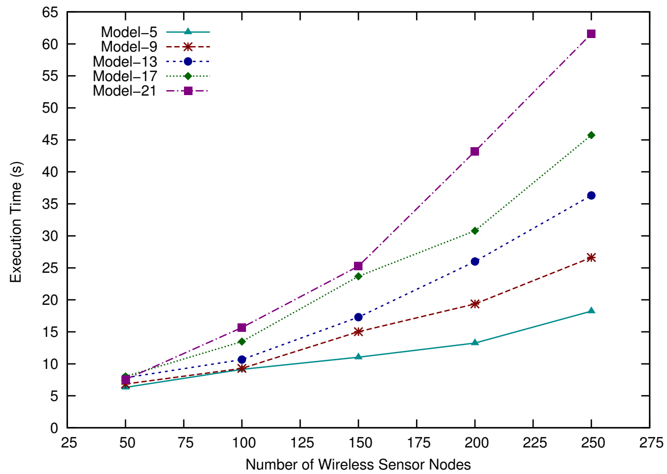


Figure 16: The Execution Time(s) vs The Number of Sensors

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.

6.3.6. The Network Lifetime

Finally, we will study the effect of increasing the primary points on the lifetime of the network. In Figure 17 and in Figure 18, network lifetime, $Lifetime95$ and $Lifetime50$ respectively, are illustrated for different network sizes.

As highlighted by figures 17 and 18, the network lifetime obviously increases when the size of the network increases, with our Model 1 that leads to the larger lifetime improvement. Comparison shows that the Model 1, which uses less number 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.

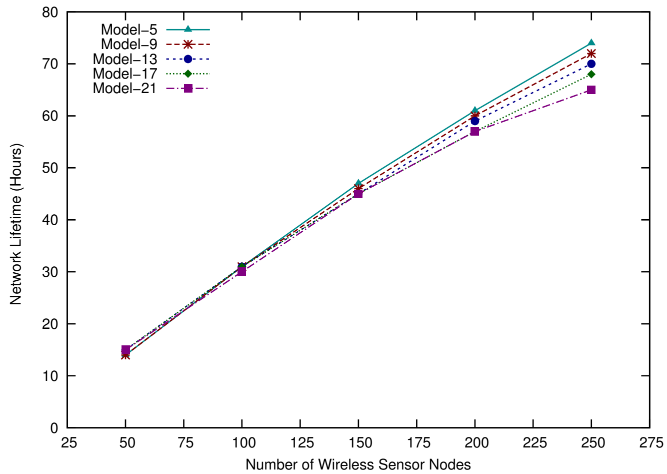


Figure 17: The Network Lifetime for $Lifetime95$

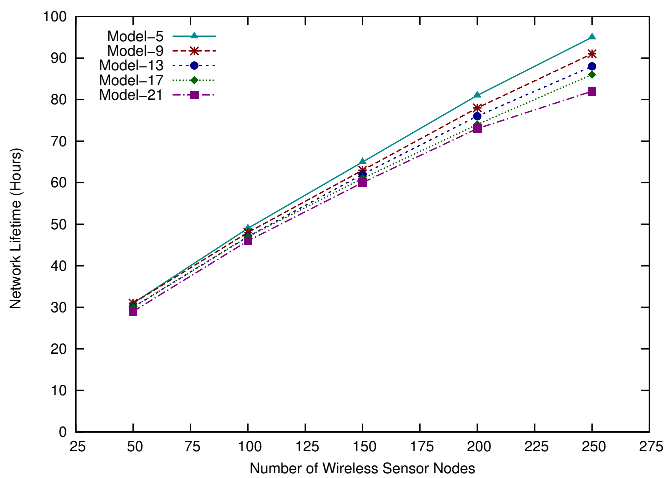


Figure 18: The Network Lifetime for $Lifetime50$

6.4. Performance Comparison for Different Approaches

Based on the results, which are conducted from previous two subsections, 6.2 and 6.3, we are found that Our DiLCO-16, and DiLCO-32 protocols with Model 2 are the best candidates to be compared with other two approches. The first approach, called DESK that proposed by [20], which is a full distributed coverage algorithm. The second approach, called GAF [32], 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.

6.4.1. Coverage Ratio

In this experiment, Figure 19 shows the average coverage ratio for 150 deployed nodes.

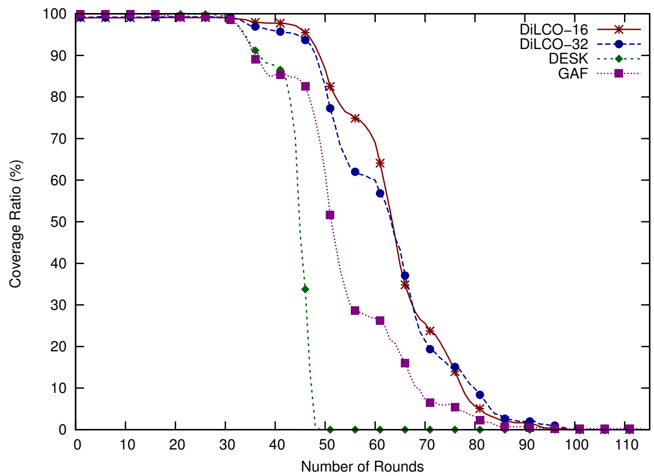


Figure 19: The coverage ratio for 150 deployed nodes

It is shown that DESK and GAF provides a a little better coverage ratio with 99.99% and 99.91% against 99.1% and 99.2% produced by DiLCO-16 and DiLCO-32 for the lowest number of rounds. This is due to the fact that our DiLCO protocol versions 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-16 and DiLCO-32 protocols maintains almost a good 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.

6.4.2. Active Sensors Ratio

It is important to have as few active nodes as possible in each round, in order to minimize the energy consumption and maximize the network lifetime. Figure 20 shows the average active nodes ratio for 150 deployed nodes.

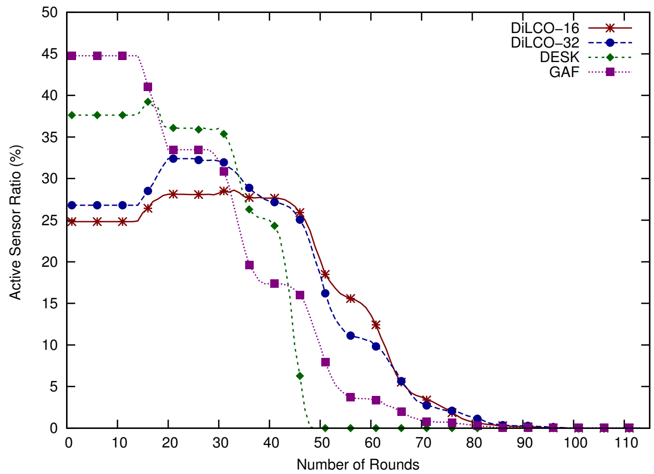


Figure 20: The active sensors ratio for 150 deployed nodes

The results presented in figure 20 show the superiority of the proposed DiLCO-16 and DiLCO-32 protocols, in comparison with the other approaches. We can observe that DESK and GAF have 37.5 % and 44.5 % active nodes and our DiLCO-16 and DiLCO-32 protocols competes perfectly with only 17.4 %, 24.8 % and 26.8 % active nodes for the first 14 rounds. Then as the number of rounds increases our DiLCO-16 and DiLCO-32 protocols have larger number of active nodes in comparison with DESK and GAF, especially from round 35^{th} because they give a better coverage ratio than other approaches. We see that the DESK and GAF have less number of active nodes beginning at the rounds 35^{th} and 32^{th} because there are many nodes are died due to the high energy consumption by the redundant nodes during the sensing phase.

6.4.3. The percentage of stopped simulation runs

The results presented in this experiment, is to show the comparison of our DiLCO-16 and DiLCO-32 protocols with other two approaches from the point of view the stopped simulation runs per round. Figure 21 illustrates the

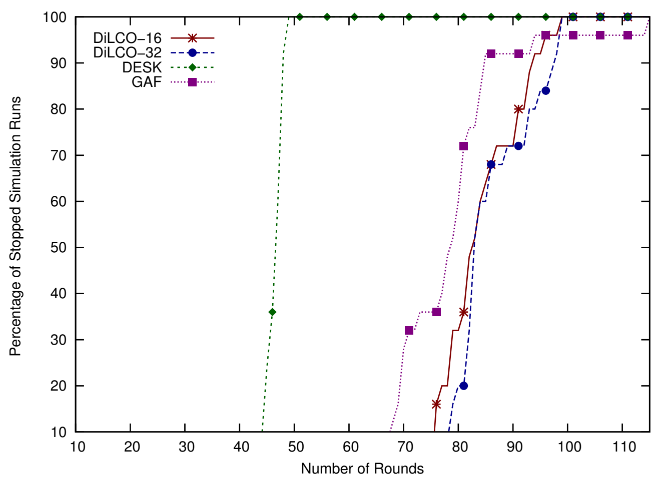


Figure 21: The percentage of stopped simulation runs compared to the number of rounds for 150 deployed nodes

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-16 and DiLCO-32 protocols have less stopped simulation runs in comparison with DESK and GAF because 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.

6.4.4. The Energy Consumption

In this experiment, we study the effect of the energy consumed by the wireless sensor network during the communication, computation, listening, active, and sleep modes for different network densities and compare it with other approaches. Figures 22 and 23 illustrate the energy consumption for different network sizes for $Lifetime95$ and $Lifetime50$.

The results show that our DiLCO-16 and DiLCO-32 protocols 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 during the different modes of sensor nodes. In fact, a distributed method on the subregions greatly

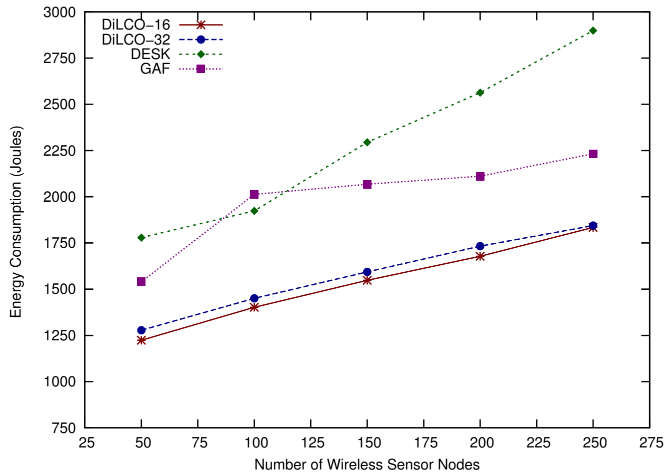


Figure 22: The Energy Consumption with $95\% - Lifetime$

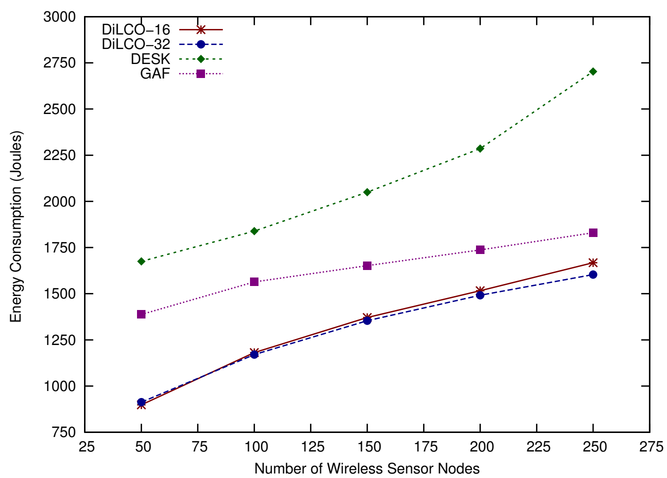


Figure 23: The Energy Consumption with $Lifetime50$

reduces the number of communications and the time of listening so thanks to the partitioning of the initial network into several independent subnetworks.

6.4.5. The Network Lifetime

In this experiment, we are observed the superiority of our DiLCO-16 and DiLCO-32 protocols against other two approaches in prolonging the network lifetime. In figures 24 and 25, network lifetime, $Lifetime95$ and $Lifetime50$ respectively, are illustrated for different network sizes.

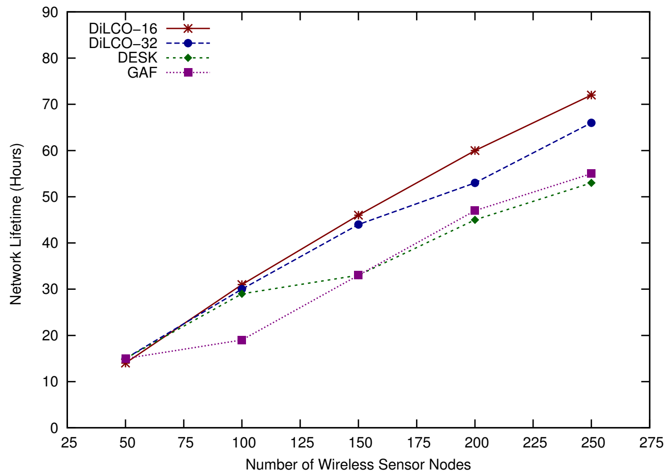


Figure 24: The Network Lifetime for $Lifetime95$

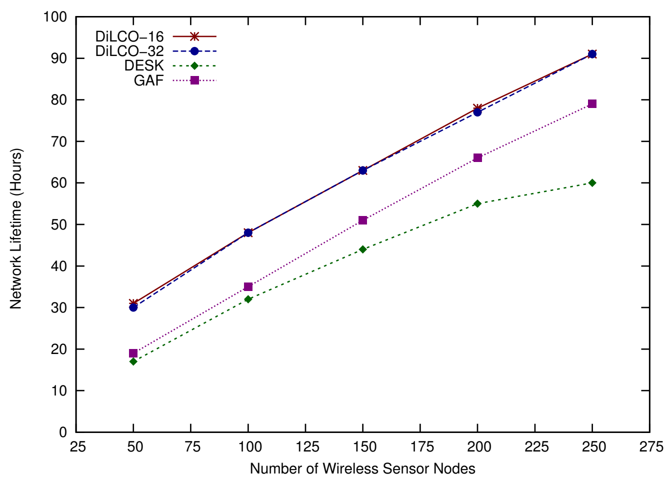


Figure 25: The Network Lifetime for $Lifetime50$

As highlighted by figures 24 and 25, the network lifetime obviously increases when the size of the network increases, with our DiLCO-16 and DiLCO-32 protocols 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-16 and DiLCO-32 protocols efficiently prolonges the network lifetime. Comparison shows that our DiLCO-16 and DiLCO-32 protocols, which are used distributed optimization over 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 DiLCO protocol for optimizing the 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 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 are proposed 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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