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Perimeter-based Coverage Optimization to Improve Lifetime in Wireless Sensor Networks

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The most important problem in a Wireless Sensor Network (WSN) is to optimize the use of its limited energy provision, so that it can fulfill its monitoring task as long as possible. Among known available approaches that can be used to improve power management, lifetime coverage optimization provides activity scheduling which ensures sensing coverage while minimizing the energy cost. We propose such an approach called Perimeter-based Coverage Optimization protocol (PeCO). It is a hybrid of centralized and distributed methods: the region of interest is first subdivided into subregions and the protocol is then distributed among sensor nodes in each subregion. The novelty of our approach lies essentially in the formulation of a new mathematical optimization model based on the perimeter coverage level to schedule sensors' activities. Extensive simulation experiments demonstrate that PeCO can offer longer lifetime coverage for WSNs in comparison with some other protocols.

Keywords: Wireless Sensor Networks, Area Coverage, Energy efficiency, Optimization, Scheduling.

1. Introduction

The continuous progress in Micro Electro-Mechanical Systems (MEMS) and wireless communication hardware has given rise to the opportunity to use large networks of tiny sensors, called Wireless Sensor Networks (WSN) (Akyildiz et al. 2002; Puccinelli and Haenggi 2005), to fulfill monitoring tasks. A WSN consists of small low-powered sensors working together by communicating with one another through multi-hop radio communications. Each node can send the data it collects in its environment, thanks to its sensor, to the user by means of sink nodes. The features of a WSN made it suitable for a wide range of application in areas such as business, environment, health, industry, military, and so on (Yick, Mukherjee, and Ghosal 2008). Typically, a sensor node contains three main components (Anastasi et al. 2009): a sensing unit able to measure physical, chemical, or biological phenomena observed in the environment; a processing unit which will process and store the collected measurements; a radio communication unit for data transmission and receiving.

The energy needed by an active sensor node to perform sensing, processing, and communication is supplied by a power supply which is a battery. This battery has a limited energy provision and it may be unsuitable or impossible to replace or recharge it in most applications. Therefore it is necessary to deploy WSN with high density in order

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to increase reliability and to exploit node redundancy thanks to energy-efficient activity scheduling approaches. Indeed, the overlap of sensing areas can be exploited to schedule alternatively some sensors in a low power sleep mode and thus save energy. Overall, the main question that must be answered is: how to extend the lifetime coverage of a WSN as long as possible while ensuring a high level of coverage? These past few years many energy-efficient mechanisms have been suggested to retain energy and extend the lifetime of the WSNs (Rault, Bouabdallah, and Challal 2014).

This paper makes the following contributions.

(1) A framework is devised to schedule nodes to be activated alternatively such that the network lifetime is prolonged while ensuring that a certain level of coverage is preserved. A key idea in the proposed framework is to exploit spatial and temporal subdivision. On the one hand, the area of interest is divided into several smaller subregions and, on the other hand, the time line is divided into periods of equal length. In each subregion the sensor nodes will cooperatively choose a leader which will schedule nodes' activities, and this grouping of sensors is similar to typical cluster architecture.

(2) A new mathematical optimization model is proposed. Instead of trying to cover a set of specified points/targets as in most of the methods proposed in the literature, we formulate an integer program based on perimeter coverage of each sensor. The model involves integer variables to capture the deviations between the actual level of coverage and the required level. Hence, an optimal schedule will be obtained by minimizing a weighted sum of these deviations.

(3) Extensive simulation experiments are conducted using the discrete event simulator OMNeT++, to demonstrate the efficiency of our protocol. We have compared the PeCO protocol to two approaches found in the literature: DESK (Vu et al. 2006) and GAF (Xu, Heidemann, and Estrin 2001), and also to our previous protocol DiLCO published in (Idrees et al. 2015). DiLCO uses the same framework as PeCO but is based on another optimization model for sensor scheduling.

The rest of the paper is organized as follows. In the next section some related work in the field is reviewed. Section 3 is devoted to the PeCO protocol description and Section 4 focuses on the coverage model formulation which is used to schedule the activation of sensor nodes. Section 5 presents simulations results and discusses the comparison with other approaches. Finally, concluding remarks are drawn and some suggestions are given for future works in Section 6.

2. Related Literature

This section summarizes some related works regarding the coverage problem and presents specific aspects of the PeCO protocol common with other literature works.

The most discussed coverage problems in literature can be classified in three categories (Li and Vasilakos 2013) according to their respective monitoring objective. Hence, area coverage (Misra, Kumar, and Obaidat 2011) means that every point inside a fixed area must be monitored, while target coverage (Yang and Chin 2014a) refers to the objective of coverage for a finite number of discrete points called targets, and barrier coverage (He et al. 2014; Kim and Cobb 2013) focuses on preventing intruders from entering into the region of interest. In (Deng, Jiguo Yu, and Chen 2012) authors transform the area coverage problem into the target coverage one taking into account the intersection points among disks of sensors nodes or between disk of sensor nodes and boundaries. In (Huang and Tseng 2005a) authors prove that if the perimeters of sensors are sufficiently covered it will be the case for the whole area. They provide an algorithm in $O(nd\ log\ d)$ time to compute the perimeter-coverage of each sensor. d denotes the maximum number of sensors that are neighbors to a sensor, and n is the total number of sensors in the network. *In PeCO protocol, instead of determining the level of coverage of a set of discrete points, our optimization model is based on checking the perimeter-coverage of each sensor to activate a minimal number of sensors.*

The major approach to extend network lifetime while preserving coverage is to divide/organize the sensors into a suitable number of set covers (disjoint or non-disjoint) (Wang 2011), where each set completely covers a region of interest, and to activate these set covers successively. The network activity can be planned in advance and scheduled for the entire network lifetime or organized in periods, and the set of active sensor nodes decided at the beginning of each period (Ling and Znati 2009). In fact, many authors propose algorithms working in such a periodic fashion (Vu 2009; Yan et al. 2008; Padmavathy and Chitra 2010). Active node selection is determined based on the problem requirements (e.g. area monitoring, connectivity, or power efficiency). For instance, Jaggi and Abouzeid (2006) address the problem of maximizing the lifetime by dividing sensors into the maximum number of disjoint subsets such that each subset can ensure both coverage and connectivity. A greedy algorithm is applied once to solve this problem and the computed sets are activated in succession to achieve the desired network lifetime. *Motivated by these works, PeCO protocol works in periods, where each period contains a preliminary phase for information exchange and decisions, followed by a sensing phase where one cover set is in charge of the sensing task.*

Various centralized and distributed approaches, or even a mixing of these two concepts, have been proposed to extend the network lifetime (Zhou, Das, and Gupta 2009). In distributed algorithms (Vu et al. 2006; Qu and Georgakopoulos 2013; Yang and Chin 2014b) each sensor decides of its own activity scheduling after an information exchange with its neighbors. The main interest of such an approach is to avoid long range communications and thus to reduce the energy dedicated to the communications. Unfortunately, since each node has only information on its immediate neighbors (usually the one-hop ones) it may make a bad decision leading to a global suboptimal solution. Conversely, centralized algorithms (Cardei and Du 2005; Zorbas et al. 2010; Pujari 2011) always provide nearly or close to optimal solution since the algorithm has a global view of the whole network. The disadvantage of a centralized method is obviously its high cost in communications needed to transmit to a single node, the base station which will globally schedule nodes' activities, data from all the other sensor nodes in the area. The price in communications can be huge since long range communications will be needed. In fact the larger the WSN, the higher the communication energy cost. *In order to be suitable for large-scale networks, in PeCO protocol the area of interest is divided into several smaller subregions, and in each one, a node called the leader is in charge of selecting the active sensors for the current period. Thus PeCO protocol is scalable and a globally distributed method, whereas it is centralized in each subregion.*

Various coverage scheduling algorithms have been developed these past few years. Many of them, dealing with the maximization of the number of cover sets, are heuristics. These heuristics involve the construction of a cover set by including in priority the sensor nodes which cover critical targets, that is to say targets that are covered by the smallest number of sensors (Berman and Calinescu 2004; Zorbas et al. 2010). Other approaches are based on mathematical programming formulations (Cardei et al. 2005; Xing, Li, and Wang 2010; Pujari 2011; Yang and Liu 2014) and dedicated techniques (solving with a branch-and-bound algorithm available in optimization solver). The problem is formulated as an optimization problem (maximization of the lifetime or number of cover sets) under target coverage and energy constraints. Column generation techniques, well-known and widely practiced techniques for solving linear programs with too many variables, have also been used (Castaño et al. 2014; Singh, Rossi, and Sevaux 2013; Deschinkel 2012).

In the PeCO protocol, each leader, in charge of a subregion, solves an integer program which has a twofold objective: minimize the overcoverage and the undercoverage of the perimeter of each sensor.

The authors in (Idrees et al. 2015) propose a Distributed Lifetime Coverage Optimization (DiLCO) protocol, which maintains the coverage and improves the lifetime in WSNs. It is an improved version of a research work presented in (Idrees et al. 2014). First, the area of interest is partitioned into subregions using a divide-and-conquer method. DiLCO protocol is then distributed on the sensor nodes in each subregion in a second step. Hence this protocol combines two techniques: a leader election in each subregion, followed by an optimization-based node activity scheduling performed by each elected leader. The proposed DiLCO protocol is a periodic protocol where each period is decomposed into 4 phases: information exchange, leader election, decision, and sensing. The simulations show that DiLCO is able to increase the WSN lifetime and provides improved coverage performance. *In the PeCO protocol, a new mathematical optimization model is proposed. Instead of trying to cover a set of specified points/targets as in DiLCO protocol, we formulate an integer program based on perimeter coverage of each sensor. The model involves integer variables to capture the deviations between the actual level of coverage and the required level. The idea is that an optimal scheduling will be obtained by minimizing a weighted sum of these deviations.*

3. The PeCO Protocol Description

3.1 *Assumptions and Models*

A WSN consisting of J stationary sensor nodes randomly and uniformly distributed in a bounded sensor field is considered. The wireless sensors are deployed in high density to ensure initially a high coverage ratio of the area of interest. We assume that all the sensor nodes are homogeneous in terms of communication, sensing, and processing capabilities and heterogeneous from the energy provision point of view. The location information is available to a sensor node either through hardware such as embedded GPS or location discovery algorithms. We consider a Boolean disk coverage model, which is the most widely used sensor coverage model in the literature, and all sensor nodes have a constant sensing range R_s. Thus, all the space points within a disk centered at a sensor with a radius equal to the sensing range are said to be covered by this sensor. We also assume that the communication range R_c satisfies $R_c \geq 2 \cdot R_s$. In fact, Zhang and Hou (2005) proved that if the transmission range fulfills the previous hypothesis, the complete coverage of a convex area implies connectivity among active nodes.

The PeCO protocol uses the same perimeter-coverage model as Huang and Tseng (2005b). It can be expressed as follows: a sensor is said to be perimeter covered if all the points on its perimeter are covered by at least one sensor other than itself. Authors Huang and Tseng (2005b) proved that a network area is k-covered (every point in the area is covered by at least k sensors) if and only if each sensor in the network is k-perimeter-covered (perimeter covered by at least k sensors).

Figure 1(a) shows the coverage of sensor node 0. On this figure, sensor 0 has nine neighbors and we have reported on its perimeter (the perimeter of the disk covered by the sensor) for each neighbor the two points resulting from the intersection of the two sensing areas. These points are denoted for neighbor i by iL and iR, respectively for left and right from a neighboring point of view. The resulting couples of intersection points subdivide the perimeter of sensor 0 into portions called arcs.

Figure 1(b) describes the geometric information used to find the locations of the left and right points of an arc on the perimeter of a sensor node u covered by a sensor node v.

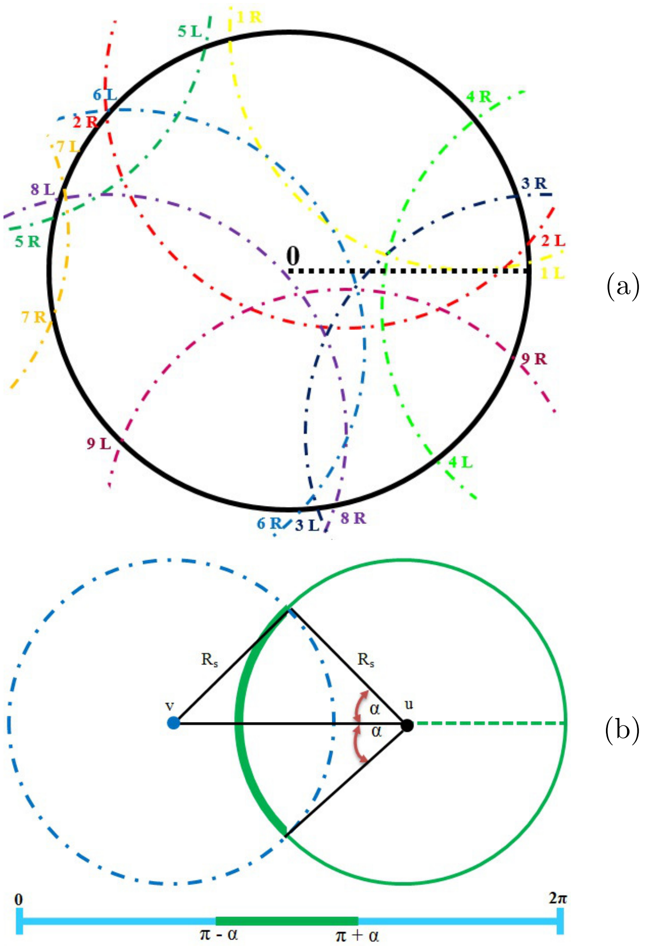

Figure 1. (a) Perimeter coverage of sensor node 0 and (b) finding the arc of u's perimeter covered by v.

Node v is supposed to be located on the west side of sensor u, with the following respective coordinates in the sensing area : (v_x, v_y) and (u_x, u_y). From the previous coordinates the euclidean distance between nodes u and v is computed as follows:

$$Dist(u, v) = \sqrt{|u_x - v_x|^2 + |u_y - v_y|^2},$$

while the angle α is obtained through the formula:

$$\alpha = \arccos\left(\frac{Dist(u, v)}{2R_s}\right).$$

The arc on the perimeter of u defined by the angular interval $[\pi - \alpha, \pi + \alpha]$ is then said to be perimeter-covered by sensor v.

Every couple of intersection points is placed on the angular interval $[0, 2\pi)$ in a counterclockwise manner, leading to a partitioning of the interval. Figure 1(a) illustrates the arcs for the nine neighbors of sensor 0 and Table 1 gives the position of the corresponding arcs in the interval $[0, 2\pi)$. More precisely, the points are ordered according to the measures of the angles defined by their respective positions. The intersection points are then visited one after another, starting from the first intersection point after point zero, and the maximum level of coverage is determined for each interval defined by two successive points. The maximum level of coverage is equal to the number of overlapping arcs. For example, between $5L$ and $6L$ the maximum level of coverage is equal to 3 (the value is

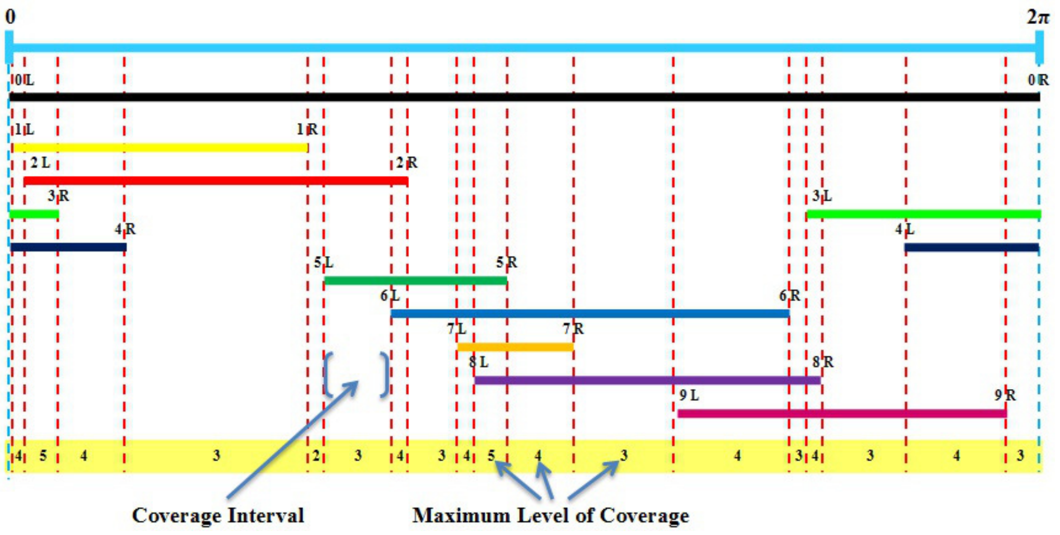

Figure 2. Maximum coverage levels for perimeter of sensor node 0.

Table 1. Coverage intervals and contributing sensors for node 0

Left point angle α	Interval left point	Interval right point	Maximum coverage level	Set of sensors involved in coverage interval				
0.0291	1L	2L	4	0	1	3	4	
0.104	2L	3R	5	0	1	3	4	2
0.3168	3R	4R	4	0	1	4	2	
0.6752	4R	1R	3	0	1	2		
1.8127	1R	5L	2	0	2			
1.9228	5L	6L	3	0	2	5		
2.3959	6L	2R	4	0	2	5	6	
2.4258	2R	7L	3	0	5	6		
2.7868	7L	8L	4	0	5	6	7	
2.8358	8L	5R	5	0	5	6	7	8
2.9184	5R	7R	4	0	6	7	8	
3.3301	7R	9R	3	0	6	8		
3.9464	9R	6R	4	0	6	8	9	
4.767	6R	3L	3	0	8	9		
4.8425	3L	8R	4	0	3	8	9	
4.9072	8R	4L	3	0	3	9		
5.3804	4L	9R	4	0	3	4	9	
5.9157	9R	1L	3	0	3	4		

highlighted in yellow at the bottom of Figure 2), which means that at most 2 neighbors can cover the perimeter in addition to node 0. Table 1 summarizes for each coverage interval the maximum level of coverage and the sensor nodes covering the perimeter. The example discussed above is thus given by the sixth line of the table.

In the PeCO protocol, the scheduling of the sensor nodes' activities is formulated with an mixed-integer program based on coverage intervals (Hung and Lui 2010). The formulation of the coverage optimization problem is detailed in Section 4. Note that when a sensor node has a part of its sensing range outside the WSN sensing field, as in Figure 3, the maximum coverage level for this arc is set to ∞ and the corresponding interval will not be taken into account by the optimization algorithm.

3.2 *Main Idea*

The WSN area of interest is, in a first step, divided into regular homogeneous subregions using a divide-and-conquer algorithm. In a second step our protocol will be executed in a distributed way in each subregion simultaneously to schedule nodes' activities for one sensing period. Sensor nodes are assumed to be deployed almost uniformly over the

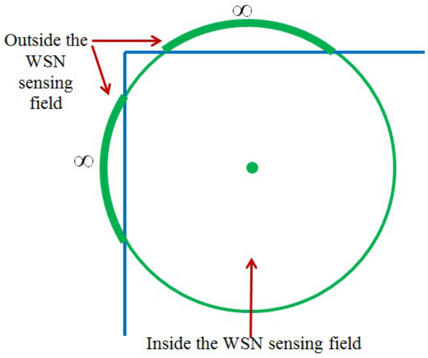

Figure 3. Sensing range outside the WSN's area of interest.

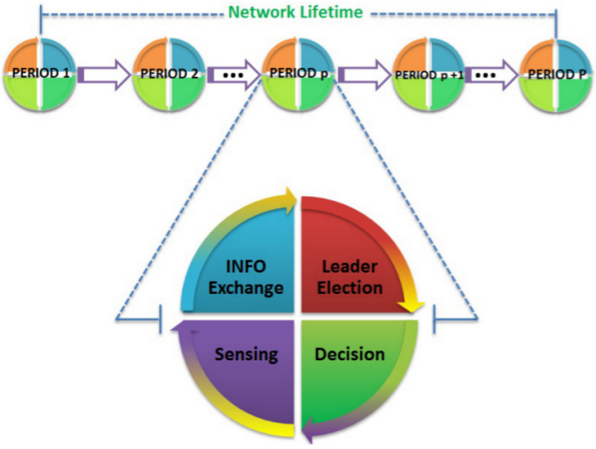

Figure 4. PeCO protocol.

region. The regular subdivision is made such that the number of hops between any pairs of sensors inside a subregion is less than or equal to 3.

As shown in Figure 4, node activity scheduling is produced by the proposed protocol in a periodic manner. Each period is divided into 4 stages: Information (INFO) Exchange, Leader Election, Decision (the result of an optimization problem), and Sensing. For each period there is exactly one set cover responsible for the sensing task. Protocols based on a periodic scheme, like PeCO, are more robust against an unexpected node failure. On the one hand, if a node failure is discovered before taking the decision, the corresponding sensor node will not be considered by the optimization algorithm. On the other hand, if the sensor failure happens after the decision, the sensing task of the network will be temporarily affected: only during the period of sensing until a new period starts, since a new set cover will take charge of the sensing task in the next period. 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 period. However, the pre-sensing phases (INFO Exchange, Leader Election, and Decision) are energy consuming, even for nodes that will not join the set cover to monitor the area. Sensing period duration is adapted according to the QoS requirements of the application.

We define two types of packets to be used by PeCO protocol:

- INFO packet: sent by each sensor node to all the nodes inside a same subregion for information exchange.
- ActiveSleep packet: sent by the leader to all the nodes in its subregion to transmit to them their respective status (stay Active or go Sleep) during sensing phase.

Five statuses are possible for a sensor node in the network:

- LISTENING: waits for a decision (to be active or not);
- COMPUTATION: executes the optimization algorithm as leader to determine the activities scheduling;
- ACTIVE: node is sensing;
- SLEEP: node is turned off;
- COMMUNICATION: transmits or receives packets.

3.3 *PeCO Protocol Algorithm*

The pseudocode implementing the protocol on a node is given below. More precisely, Algorithm 1 gives a brief description of the protocol applied by a sensor node s_k where k is the node index in the WSN.

Algorithm 1: PeCO pseudocode

```
if $RE_k \geq E_{th}$ then
    $s_k.status$ = COMMUNICATION;
    Send $INFO()$ packet to other nodes in subregion;
    Wait $INFO()$ packet from other nodes in subregion;
    Update K.CurrentSize;
    LeaderID = Leader election;
    if $s_k.ID = LeaderID$ then
        $s_k.status$ = COMPUTATION;
        if $s_k.ID$ is Not previously selected as a Leader then
            Execute the perimeter coverage model;
        if ($s_k.ID$ is the same Previous Leader) and
        (K.CurrentSize = K.PreviousSize) then
            Use the same previous cover set for current sensing stage;
        else
            Update $a^j_{ik}$; prepare data for IP Algorithm;
            $\{(X_1, \dots, X_l, \dots, X_K)\}$ = Execute Integer Program Algorithm($K$);
            K.PreviousSize = K.CurrentSize;
        $s_k.status$ = COMMUNICATION;
        Send $ActiveSleep()$ to each node $l$ in subregion;
        Update $RE_k$;
    else
        $s_k.status$ = LISTENING;
        Wait $ActiveSleep()$ packet from the Leader;
        Update $RE_k$;
else
    Exclude $s_k$ from entering in the current sensing stage;
```

In this algorithm, $K.CurrentSize$ and $K.PreviousSize$ respectively represent the current number and the previous number of living nodes in the subnetwork of the subregion. At the beginning of the first period $K.PreviousSize$ is initialized to zero. Initially, the sensor node checks its remaining energy RE_k, which must be greater than a threshold E_{th} in order to participate in the current period. Each sensor node determines its position and its subregion using an embedded GPS or a location discovery algorithm. After that, all the sensors collect position coordinates, remaining energy, sensor node ID, and the number of their one-hop live neighbors during the information exchange. The sensors inside a same region cooperate to elect a leader. The selection criteria for the leader are (in order of priority):

(1) larger number of neighbors;
(2) larger remaining energy;
(3) and then in case of equality, larger index.

Once chosen, the leader collects information to formulate and solve the integer program which allows to construct the set of active sensors in the sensing stage.

4. Perimeter-based Coverage Problem Formulation

In this section, the perimeter-based coverage problem is mathematically formulated. It has been proved to be a NP-hard problem by (Hung and Lui 2010). Authors study the coverage of the perimeter of a large object requiring to be monitored. For the proposed formulation in this paper, the large object to be monitored is the sensor itself (or more precisely its sensing area).

The following notations are used throughout the section.

First, the following sets:

- S represents the set of sensor nodes;
- $A \subseteq S$ is the subset of alive sensors;
- I_j designates the set of coverage intervals (CI) obtained for sensor j.

I_j refers to the set of coverage intervals which have been defined according to the method introduced in subsection 3.1. For a coverage interval i, let a^j_{ik} denote the indicator function of whether sensor k is involved in coverage interval i of sensor j, that is:

$$a^j_{ik} = \begin{cases} 1 \text{ if sensor } k \text{ is involved in the} \\ \quad \text{coverage interval } i \text{ of sensor } j, \\ 0 \text{ otherwise.} \end{cases} \tag{1}$$

Note that $a^k_{ik} = 1$ by definition of the interval.

Second, several variables are defined. Hence, each binary variable X_k determines the activation of sensor k in the sensing phase ($X_k = 1$ if the sensor k is active or 0 otherwise). M^j_i is a variable which measures the undercoverage for the coverage interval i corresponding to sensor j. In the same way, the overcoverage for the same coverage interval is given by the variable V^j_i.

To sustain a level of coverage equal to l all along the perimeter of sensor j, at least l sensors involved in each coverage interval $i \in I_j$ of sensor j have to be active. According to the previous notations, the number of active sensors in the coverage interval i of sensor j is given by $\sum_{k \in A} a^j_{ik} X_k$. To extend the network lifetime, the objective is to activate a minimal number of sensors in each period to ensure the desired coverage level. As the number of alive sensors decreases, it becomes impossible to reach the desired level of coverage for all coverage intervals. Therefore variables M^j_i and V^j_i are introduced as a measure of the deviation between the desired number of active sensors in a coverage interval and the effective number. And we try to minimize these deviations, first to force the activation of a minimal number of sensors to ensure the desired coverage level, and if the desired level cannot be completely satisfied, to reach a coverage level as close as possible to the desired one.

The coverage optimization problem can then be mathematically expressed as follows:

$$
\begin{aligned}
&\text{Minimize } \sum_{j \in S} \sum_{i \in I_j} (\alpha^j_i \; M^j_i + \beta^j_i \; V^j_i) \\
&\text{Subject to:} \\
&\quad \sum_{k \in A} (a^j_{ik} \; X_k) + M^j_i \geq l \quad \forall i \in I_j, \forall j \in S \\
&\quad \sum_{k \in A} (a^j_{ik} \; X_k) - V^j_i \leq l \quad \forall i \in I_j, \forall j \in S \\
&\quad X_k \in \{0,1\}, \forall k \in A \\
&\quad M^j_i, V^j_i \in \mathbb{R}^+
\end{aligned}
\tag{2}
$$

If a given level of coverage l is required for one sensor, the sensor is said to be undercovered (respectively overcovered) if the level of coverage of one of its CI is less (respectively greater) than l. If the sensor j is undercovered, there exists at least one of its CI (say i) for which the number of active sensors (denoted by l^i) covering this part of the perimeter is less than l and in this case : $M^j_i = l - l^i$, $V^j_i = 0$. Conversely, if the sensor j is overcovered, there exists at least one of its CI (say i) for which the number of active sensors (denoted by l^i) covering this part of the perimeter is greater than l and in this case: $M^j_i = 0$, $V^j_i = l^i - l$.

α^j_i and β^j_i are nonnegative weights selected according to the relative importance of satisfying the associated level of coverage. For example, weights associated with coverage intervals of a specified part of a region may be given by a relatively larger magnitude than weights associated with another region. This kind of mixed-integer program is inspired from the model developed for brachytherapy treatment planning for optimizing dose distribution (Lee et al. 1999). The choice of the values for variables α and β should be made according to the needs of the application. α should be large enough to prevent undercoverage and so to reach the highest possible coverage ratio. β should be large enough to prevent overcoverage and so to activate a minimum number of sensors. The mixed-integer program must be solved by the leader in each subregion at the beginning of each sensing phase, whenever the environment has changed (new leader, death of some sensors). Note that the number of constraints in the model is constant (constraints of coverage expressed for all sensors), whereas the number of variables X_k decreases over periods, since only alive sensors (sensors with enough energy to be alive during one sensing phase) are considered in the model.

5. Performance Evaluation and Analysis

5.1 *Simulation Settings*

The WSN area of interest is supposed to be divided into 16 regular subregions and we use the same energy consumption model as in our previous work (Idrees et al. 2015). Table 2 gives the chosen parameters settings.

To obtain experimental results which are relevant, simulations with five different node densities going from 100 to 300 nodes were performed considering each time 25 randomly generated networks. The nodes are deployed on a field of interest of (50×25) m^2 in such a way that they cover the field with a high coverage ratio. Each node has an initial energy level, in Joules, which is randomly drawn in the interval $[500 - 700]$. If its energy

Table 2. Relevant parameters for network initialization

Parameter	Value
Sensing field	$(50 \times 25)\ m^2$
WSN size	100, 150, 200, 250, and 300 nodes
Initial energy	in range 500-700 Joules
Sensing period	duration of 60 minutes
E_{th}	36 Joules
R_s	5 m
R_c	10 m
α_i^j	0.6
β_i^j	0.4

provision reaches a value below the threshold $E_{th} = 36$ Joules, the minimum energy needed for a node to stay active during one period, it will no longer participate in the coverage task. This value corresponds to the energy needed by the sensing phase, obtained by multiplying the energy consumed in the active state (9.72 mW) with the time in seconds for one period (3600 seconds), and adding the energy for the pre-sensing phases. According to the interval of initial energy, a sensor may be active during at most 20 periods. Information exchange to update the coverage is executed every hour, but the length of the sensing period could be reduced and adapted dynamically. On the one hand a small sensing period would allow to be more reliable but would have result in higher communication costs. On the other hand the choice of a long duration may cause problems in case of nodes failure during the sensing period.

The values of α_i^j and β_i^j have been chosen to ensure a good network coverage and a longer WSN lifetime. Higher priority is given to the undercoverage (by setting the α_i^j with a larger value than β_i^j) so as to prevent the non-coverage for the interval i of the sensor j. On the other hand, β_i^j is assigned to a value which is slightly lower so as to minimize the number of active sensor nodes which contribute in covering the interval. Subsection 5.2.5 investigates more deeply how the values of both parameters affect the performance of PeCO protocol.

The following performance metrics are used to evaluate the efficiency of the approach.

- **Network Lifetime**: the lifetime is defined as the time elapsed until the coverage ratio falls below a fixed threshold. $Lifetime_{95}$ and $Lifetime_{50}$ denote, respectively, the amount of time during which is guaranteed a level of coverage greater than 95% and 50%. The WSN can fulfill the expected monitoring task until all its nodes have depleted their energy or if the network is no more connected. This last condition is crucial because without network connectivity a sensor may not be able to send to a base station an event it has sensed.
- **Coverage Ratio (CR)** : it measures how well the WSN is able to observe the area of interest. In our case, the sensor field is discretized as a regular grid, which yields the following equation:

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

  where n is the number of covered grid points by active sensors of every subregions during the current sensing phase and N is total number of grid points in the sensing field. A layout of $N = 51 \times 26 = 1326$ grid points is considered in the simulations.
- **Active Sensors Ratio (ASR)**: a major objective of our protocol is to activate as few nodes as possible, in order to minimize the communication overhead and maximize

the WSN lifetime. The active sensors ratio is defined as follows:

$$\text{ASR}(\%) = \frac{\sum\limits_{r=1}^{R} |A_r^p|}{|J|} \times 100$$

where $|A_r^p|$ is the number of active sensors in the subregion r in the sensing period p, R is the number of subregions, and $|J|$ is the number of sensors in the network.

- **Energy Consumption (EC)**: energy consumption can be seen as the total energy consumed by the sensors during $Lifetime_{95}$ or $Lifetime_{50}$, divided by the number of periods. The value of EC is computed according to this formula:

$$\text{EC} = \frac{\sum\limits_{p=1}^{P} \left(E_p^{\text{com}} + E_p^{\text{list}} + E_p^{\text{comp}} + E_p^{a} + E_p^{s} \right)}{P},$$

where P corresponds to the number of periods. The total energy consumed by the sensors comes through taking into consideration four main energy factors. The first one, denoted E_p^{com}, represents the energy consumption spent by all the nodes for wireless communications during period p. E_p^{list}, the next factor, corresponds to the energy consumed by the sensors in LISTENING status before receiving the decision to go active or sleep in period p. E_p^{comp} refers to the energy needed by all the leader nodes to solve the integer program during a period (COMPUTATION status). Finally, E_p^a and E_p^s indicate the energy consumed by the WSN during the sensing phase (*active* and *sleeping* nodes).

5.2 *Simulation Results*

In order to assess and analyze the performance of our protocol we have implemented PeCO protocol in OMNeT++ (Varga 2003) simulator. The simulations were run on a DELL laptop with an Intel Core i3 2370 M (1.8 GHz) processor (2 cores) whose MIPS (Million Instructions Per Second) rate is equal to 35330. To be consistent with the use of a sensor node based on Atmels AVR ATmega103L microcontroller (6 MHz) having a MIPS rate equal to 6, the original execution time on the laptop is multiplied by 2944.2 $\left(\frac{35330}{2} \times \frac{1}{6}\right)$. Energy consumption is calculated according to the power consumption values, in milliWatt per second, given in Table 3 based on the energy model proposed in (Vu et al. 2006).

Table 3. Power consumption values

Sensor status	MCU	Radio	Sensor	*Power (mW)*
LISTENING	On	On	On	20.05
ACTIVE	On	Off	On	9.72
SLEEP	Off	Off	Off	0.02
COMPUTATION	On	On	On	26.83
Energy needed to send or receive a 2-bit content message				0.515

The modeling language for Mathematical Programming (AMPL) (Fourer, Gay, and Kernighan November 12, 2002) is used to generate the integer program instance in a standard format, which is then read and solved by the optimization solver GLPK (GNU linear Programming Kit available in the public domain) (Makhorin 2012) through a Branch-and-Bound method. In practice, executing GLPK on a sensor node is obviously intractable due to the huge memory use. Fortunately, to solve the optimization problem we could use commercial solvers like CPLEX (CPLEX 2010) which are less memory consuming and more efficient, or implement a lightweight heuristic. For example, for a WSN of 200 sensor nodes, a leader node has to deal with constraints induced by about 12 sensor nodes. In that case, to solve the optimization problem a memory consumption of more than 1 MB can be observed with GLPK, whereas less than 300 kB would be needed with CPLEX.

Besides PeCO, three other protocols will be evaluated for comparison purposes. The first one, called DESK, is a fully distributed coverage algorithm proposed by (Vu et al. 2006). The second one, called GAF (Xu, Heidemann, and Estrin 2001), consists in dividing the monitoring area into fixed squares. Then, during the decision phase, in each square, one sensor is chosen to remain active during the sensing phase. The last one, the DiLCO protocol (Idrees et al. 2015), is an improved version of a research work we presented in (Idrees et al. 2014). Let us notice that PeCO and DiLCO protocols are based on the same framework. In particular, the choice for the simulations of a partitioning in 16 subregions was made because it corresponds to the configuration producing the best results for DiLCO. Of course, this number of subregions should be adapted according to the size of the area of interest and the number of sensors. The protocols are distinguished from one another by the formulation of the integer program providing the set of sensors which have to be activated in each sensing phase. DiLCO protocol tries to satisfy the coverage of a set of primary points, whereas PeCO protocol objective is to reach a desired level of coverage for each sensor perimeter. In our experimentations, we chose a level of coverage equal to one ($l = 1$).

5.2.1 Coverage Ratio

Figure 5 shows the average coverage ratio for 200 deployed nodes obtained with the four protocols. DESK, GAF, and DiLCO provide a slightly better coverage ratio with respectively 99.99%, 99.91%, and 99.02%, compared to the 98.76% produced by PeCO for the first periods. This is due to the fact that at the beginning LiCO and PeCO protocols put to sleep status more redundant sensors (which slightly decreases the coverage ratio), while the three other protocols activate more sensor nodes. Later, when the number of periods is beyond 70, it clearly appears that PeCO provides a better coverage ratio and keeps a coverage ratio greater than 50% for longer periods (15 more compared to DiLCO, 40 more compared to DESK). The energy saved by PeCO in the early periods allows later a substantial increase of the coverage performance.

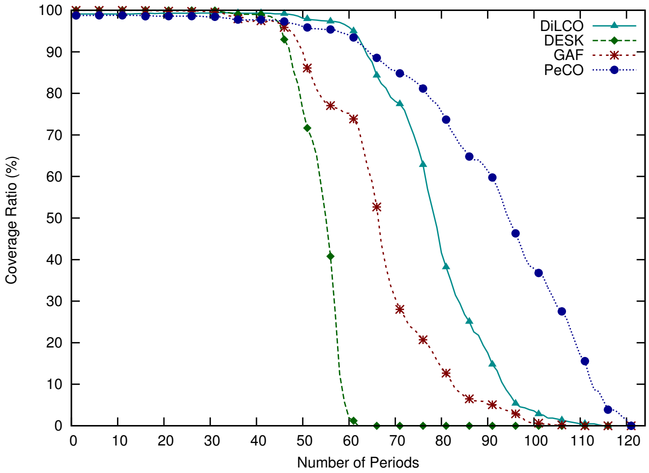

Figure 5. Coverage ratio for 200 deployed nodes.

5.2.2 Active Sensors Ratio

Having the less active sensor nodes in each period is essential to minimize the energy consumption and thus to maximize the network lifetime. Figure 6 shows the average active nodes ratio for 200 deployed nodes. We observe that DESK and GAF have 30.36 % and 34.96 % active nodes for the first fourteen rounds, and DiLCO and PeCO protocols compete perfectly with only 17.92 % and 20.16 % active nodes during the same time interval. As the number of periods increases, PeCO protocol has a lower number of active nodes in comparison with the three other approaches and exhibits a slow decrease, while keeping a greater coverage ratio as shown in Figure 5.

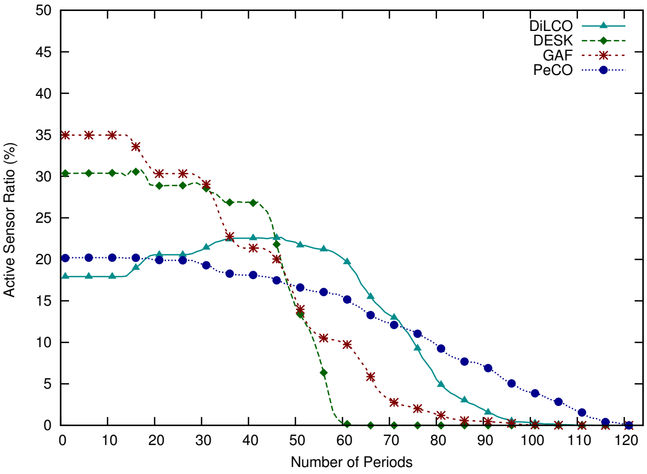

Figure 6. Active sensors ratio for 200 deployed nodes.

5.2.3 Energy Consumption

The effect of the energy consumed by the WSN during the communication, computation, listening, active, and sleep status is studied for different network densities and the four approaches compared. Figures 7(a) and (b) illustrate the energy consumption for different network sizes and for $Lifetime95$ and $Lifetime50$. The results show that PeCO protocol is the most competitive from the energy consumption point of view. As shown by both figures, PeCO consumes much less energy than the other methods. One might think that the resolution of the integer program is too costly in energy, but the results show that it is very beneficial to lose a bit of time in the selection of sensors to activate. Indeed the optimization program allows to reduce significantly the number of active sensors and so the energy consumption while keeping a good coverage level. Let us notice that the energy overhead when increasing network size is the lowest with PeCO.

5.2.4 Network Lifetime

We observe the superiority of both PeCO and DiLCO protocols in comparison with the two other approaches in prolonging the network lifetime. In Figures 8(a) and (b), $Lifetime95$ and $Lifetime50$ are shown for different network sizes. As can be seen in these figures, the lifetime increases with the size of the network, and it is clearly largest for DiLCO and PeCO protocols. For instance, for a network of 300 sensors and coverage ratio greater than 50%, we can see on Figure 8(b) that the lifetime is about twice longer with PeCO compared to DESK protocol. The performance difference is more obvious in Figure 8(b) than in Figure 8(a) because the gain induced by our protocols increases with time, and the lifetime with a coverage over 50% is far longer than with 95%.

Figure 9 compares the lifetime coverage of DiLCO and PeCO protocols for different coverage ratios. We denote by Protocol/50, Protocol/80, Protocol/85, Protocol/90, and

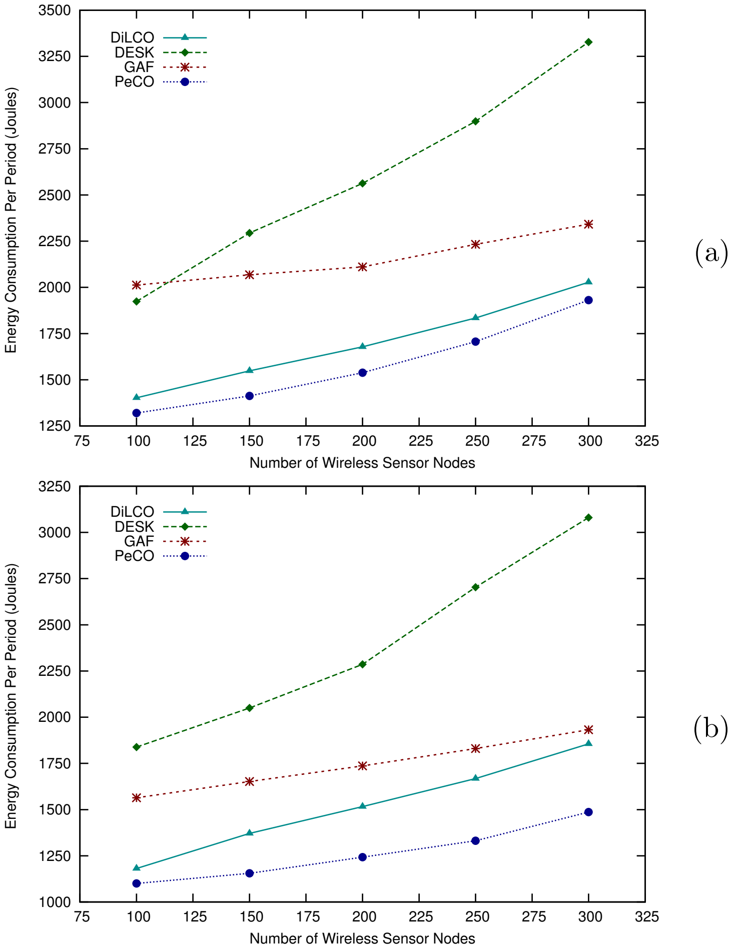

Figure 7. Energy consumption per period for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$.

Protocol/95 the amount of time during which the network can satisfy an area coverage greater than 50%, 80%, 85%, 90%, and 95% respectively, where the term Protocol refers to DiLCO or PeCO. Indeed there are applications that do not require a 100% coverage of the area to be monitored. PeCO might be an interesting method since it achieves a good balance between a high level coverage ratio and network lifetime. PeCO always outperforms DiLCO for the three lower coverage ratios, moreover the improvements grow with the network size. DiLCO is better for coverage ratios near 100%, but in that case PeCO is not ineffective for the smallest network sizes.

5.2.5 Impact of α and β on PeCO's performance

Table 4 shows network lifetime results for different values of α and β, and a network size equal to 200 sensor nodes. On the one hand, the choice of $\beta \gg \alpha$ prevents the overcoverage, and so limit the activation of a large number of sensors, but as α is low, some areas may be poorly covered. This explains the results obtained for *Lifetime50* with $\beta \gg \alpha$: a large number of periods with low coverage ratio. On the other hand, when we choose $\alpha \gg \beta$, we favor the coverage even if some areas may be overcovered, so high coverage ratio is reached, but a large number of sensors are activated to achieve this goal. Therefore network lifetime is reduced. The choice $\alpha = 0.6$ and $\beta = 0.4$ seems to achieve the best compromise between lifetime and coverage ratio. That explains why we have chosen this setting for the experiments presented in the previous subsections.

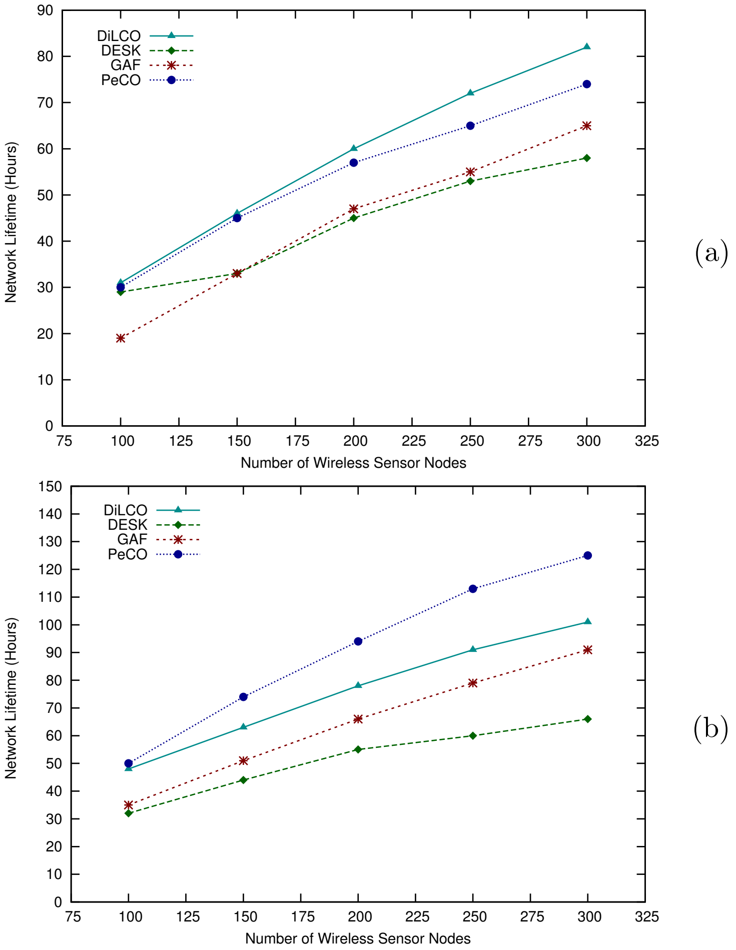

Figure 8. Network Lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$.

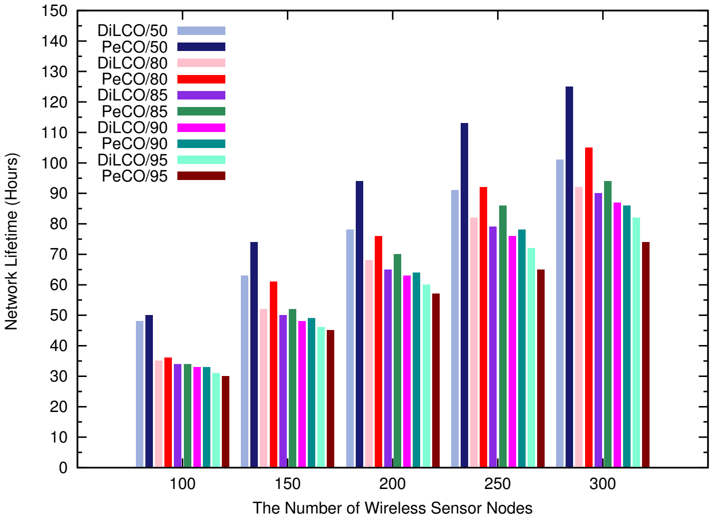

Figure 9. Network lifetime for different coverage ratios.

6. Conclusion and Future Works

In this paper we have studied the problem of perimeter coverage optimization in WSNs. We have designed a new protocol, called Perimeter-based Coverage Optimization, which schedules nodes' activities (wake up and sleep stages) with the objective of maintaining

Table 4. The impact of α and β on PeCO's performance

α	β	$Lifetime_{50}$	$Lifetime_{95}$
0.0	1.0	151	0
0.1	0.9	145	0
0.2	0.8	140	0
0.3	0.7	134	0
0.4	0.6	125	0
0.5	0.5	118	30
0.6	**0.4**	**94**	**57**
0.7	0.3	97	49
0.8	0.2	90	52
0.9	0.1	77	50
1.0	0.0	60	44

a good coverage ratio while maximizing the network lifetime. This protocol is applied in a distributed way in regular subregions obtained after partitioning the area of interest in a preliminary step. It works in periods and is based on the resolution of an integer program to select the subset of sensors operating in active status for each period. Our work is original in so far as it proposes for the first time an integer program scheduling the activation of sensors based on their perimeter coverage level, instead of using a set of targets/points to be covered. Several simulations have been carried out to evaluate the proposed protocol. The simulation results show that PeCO is more energy-efficient than other approaches, with respect to lifetime, coverage ratio, active sensors ratio, and energy consumption.

We plan to extend our framework so that the schedules are planned for multiple sensing periods. We also want to improve the integer program to take into account heterogeneous sensors from both energy and node characteristics point of views. Finally, it would be interesting to implement PeCO protocol using a sensor-testbed to evaluate it in real world applications.

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