Distributed Coverage Optimization Protocol to Improve the Lifetime in Heterogeneous Energy Wireless Sensor Networks

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***Abstract*—One of the fundamental challenges in Wireless Sensor Networks (WSNs) is Coverage preservation and extension of network lifetime continuously and effectively during monitoring a certain geographical area.In this paper a distributed coverage optimization protocol to improve the lifetime in in Heterogeneous Energy Wireless Sensor Networks is proposed. The area of interest is divided into subregions using Divide-and-conquer method and an activity scheduling for sensor nodes is planned for each subregion.Our protocol is distributed in each subregion. It divides the network lifetime into activity rounds. In each round a small number of active nodes is selected to ensure coverage.Each round includes four phases: INFO Exchange, Leader election, decision and sensing.Simulation results show that the proposed protocol can prolong the network lifetime and improve network coverage effectively.**

I. Introduction

Recent years have witnessed significant advances in wireless sensor networks which emerge as one of the most promising technologies for the 21st century [3]. In fact, they present huge potential in several domains ranging from health care applications to military applications. A sensor network is composed of a large number of tiny sensing devices deployed in a region of interest. Each device has processing and wireless communication capabilities, which enable to sense its environment, to compute, to store information and to deliver report messages to a base station. One of the main design challenges in Wireless Sensor Networks (WSN) is to prolong the system lifetime, while achieving acceptable quality of service for applications. Indeed, sensor nodes have limited resources in terms of memory, energy and computational powers.

Since sensor nodes have limited battery life and without being able to replace batteries, especially in remote and hostile environments, it is desirable that a WSN should be deployed with high density and thus redundancy can be exploited to increase the lifetime of the network. In such a high density network, if all sensor nodes were to be activated at the same time, the lifetime would be reduced. Consequently, future software may need to adapt appropriately to achieve acceptable quality of service for applications. In this paper we concentrate on area coverage problem, with the objective of maximizing the network lifetime by using an adaptive scheduling. Area of interest is divided into subregions and an activity scheduling for sensor nodes is planned for each subregion. Our scheduling scheme works in period which includes a discovery phase to exchange information between sensors of the subregion, then a sensor is chosen in suitable manner to carry out a coverage strategy. This coverage strategy involves the resolution of an integer program which provides the activation of the sensors for the t next round.

The remainder of the paper is organized as follows. Section II reviews the related work in the field. Section III is devoted to the scheduling strategy for energy-efficient coverage. Section IV gives the coverage model formulation which is used to schedule the activation of sensors. Section V shows the simulation results conducted on OMNET++, that fully demonstrate the usefulness of the proposed approach. Finally, we give concluding remarks in Section VI.

II. RELATED WORK

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

Coverage

The most discussed coverage problems in literature can be classified into two types [] : area coverage and targets coverage. An area coverage problem is to find a minimum number of sensors to work such that each physical point in the area is monitored by at least a working sensor. Target coverage problem is to cover only a finite number of discrete points called targets. Our work will concentrate on the area coverage by design and implement a strategy which efficiently select the active nodes that must maintain both sensing coverage and network connectivity and in the same time improve the lifetime of the wireless sensor network. But requiring that all physical points are covered may be too strict, specially where the sensor network is not dense. Our approach represents an area covered by a sensor as a set of principle points and tries to maximize the total number of principles points that are covered in each round, while minimizing overcoverage (points covered by multiple active sensors simultaneously).

Lifetime

Various definitions exist for the lifetime of a sensor network. Main definitions proposed in the literature are related to the remaining energy of the nodes [] or to the percentage of coverage []. The lifetime of the network is mainly defined as the amount of time that 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 our simulation we assume that the network is alive until all sensor nodes are died and we measure the coverage ratio during the process.

Activity scheduling
Activity scheduling is to schedule the activation and deactivation of nodes 'sensor units. The basic objective is to decide which sensors are in which states (active or sleeping mode) and for how long a time such that the application coverage requirement can be guaranteed and network lifetime can be prolonged. Various approaches, including centralized, distributed and localized algorithms, have been proposed for activity scheduling. In the 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 (node or base station) informs every sensor of the time intervals to be activated.

Distributed approaches

Some distributed algorithms have been developed in [30], [31], [32], [34], [35]. Distributed algorithms typically operate in roundsf predetermined duration. At the beginning of each round, a sensor exchange information with its neighbors and makes a decision to either turn on or go to sleep for the round. This decision is basically based on simple greedy criteria like the largest uncovered area [9], maximum uncovered targets [10]. In [31], the sheduling scheme is divided into rounds, where each round has a self-scheduling phase followed by a sensing phase. Each sensor broadcasts a message to its neighbors containing node ID and node location at the beginning of each round. Sensor determines its status by a rule named off-duty eligible rule which tells him to turn off if its sensing area is covered by its neighbors. A back-off scheme is introduced to let each sensor delay the decision process with a random period of time, in order to avoid that nodes make conflicting decisions simultaneously and that a part of the area is no longer covered. [11] propose a model for capturing the dependencies between different cover sets and propose localized heuristic based on this dependency. The algorithm consists of two phases, an initial setup phase during which each sensor calculates and prioritize the covers and a sensing phase during which each sensor first decides its on/off status and then remains on or off for the rest of the duration. Authors in [37] propose a novel distributed heuristic named distributed Energy-efficient Scheduling for k-coverage (DESK) so that the energy consumption among all the sensors is balanced, and network lifetime is maximized while the coverage requirements being maintained. This algorithm works in round, requires only 1-sensing-hop-neigbor information, and a sensor decides its status (active/sleep) based on its perimeter coverage computed through the k-Non-Unit-disk coverage algorithm proposed in [33].

Some others approaches do not consider synchronized and predetermined period of time where the sensors are active or not. Each sensor maintains its own timer and its time wake-up is randomized [32] or regulated [26] over time.

Centralized approaches
Power efficient centralized schemes differ according to several criteria [21], such as the coverage objective (target coverage or area coverage), the node deployment method (random or deterministic) and the heterogeneity of sensor nodes (common sensing range, common battery lifetime). The major approach is to divide/organize the sensors into a suitable number of set covers where each set completely covers an interest region and to activate these set covers successively.

First algorithms proposed in the literature consider that the cover sets are disjoint: a sensor node appears in exactly one of the generated cover sets. For instance Slijepcevic and Potkonjak [5] propose an algorithm which allocates sensor nodes in mutually independent sets to monitor an area divided into several fields. Their algorithm constructs a cover set by including in priority the sensor nodes which cover critical fields, that is to say fields that are covered by the smallest number of sensors. The time complexity of their heuristic is $O(n^2)$ where n is the number of sensors. [25] present a graph coloring technique to achieve energy savings by organizing the sensor nodes into a maximum number of disjoint dominating sets which are activated successively. The dominating sets do not guarantee the coverage of the whole region of interest. Abrams et al.[23] design three approximation algorithms for a variation of the set k-cover problem, where the objective is to partition the sensors into covers such that the number of covers that include an area, summed over all areas, is maximized. Their work builds upon previous work in [5] and the generated cover sets do not provide complete coverage of the monitoring zone.

In [6], the authors propose a heuristic to compute the disjoint set covers (DSC). In order to compute the maximum number of covers, they first transform DSC into a maximum-flow problem , which is then formulated as a mixed integer programming problem (MIP). Based on the solution of the MIP, they design a heuristic to compute the final number of covers. The results show a slight performance improvement in terms of the number of produced DSC in comparison to [5] but it incurs higher execution time due to the complexity of the mixed integer programming resolution. Zorbas et al. [24] present B{GOP}, a centralized coverage algorithm introducing sensor candidate categorisation depending on their coverage status and the notion of critical target to call targets that are associated with a small number of sensors. The total running time of their heuristic is $0(mn^2)$ where n is the number of sensors, and m the number of targets. Compared to algorithm's results of Slijepcevic and Potkonjak [5], their heuristic produces more cover sets with a slight growth rate in execution time.

In the case of non-disjoint algorithms [22], sensors may participate in more than one cover set. In some cases this may prolong the lifetime of the network in comparison to the disjoint cover set algorithms but designing algorithms for non-disjoint cover sets generally incurs a higher order of complexity. Moreover in case of a sensor's failure, non-disjoint scheduling policies are less resilient and less reliable because a sensor may be involved in more than one cover sets. For instance, Cardei et al. [27] present a linear programming (LP) solution and a greedy approach to extend the sensor network lifetime by organizing the sensors into a maximal number of non-disjoint cover sets. Simulation results show that by allowing sensors to participate in multiple sets, the network lifetime increases compared with related work [6]. In [28], the authors have formulated the lifetime problem and suggested another (LP) technique to solve this problem. A centralized provably near optimal solution based on the Garg-Könemann algorithm [29] is also proposed.

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

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

III. DISTRIBUTED COVERAGE MODEL

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

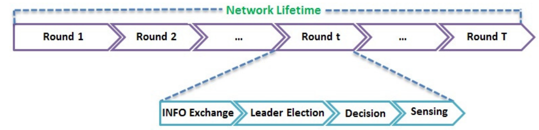


Fig. 1: Multi-Round Coverage Protocol

Each round is divided into 4 phases : INFO Exchange, Leader Election, Decision, and Sensing. For each round there is exactly one set cover responsible for sensing task. This protocol is more reliable against the unexpectedly node failure because it works into rounds,and if the node failure detected before taking the decision, the node will not participate in decision and if the the node failure obtain after the decision the sensing task of the network will be affected temporarily only during the period of sensing until starting new round, 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 the information (including their residual energy) at the beginning of each round. However, the preprocessing phase (INFO Exchange, leader Election, Decision) are energy consuming for some nodes even when they not join the network to monitor the area. We describe each phase in more detail.

A. *INFO Exchange Phase*

Each sensor node j sends its position, remaining energy RE_j, number of local neighbours NBR_j to all wireless sensor nodes in its subregion by using INFO packet and listen 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.

B. *Leader Election Phase*

This step includes choosing the Wireless Sensor Node Leader (WSNL) which will be responsible of executing coverage algorithm to choose the list of active sensor nodes that contribute in covering the subregion. The WSNL will be chosen based on the number of local neighbours NBR_j of sensor node s_j and it's remaining energy RE_j. If we have more than one node has the same NBR_j and RE_j, this leads to choose WSNL based on the largest index among them. Each subregion in the area of interest will select its WSNL independently for each round.

C. *Decision Phase*

The WSNL will execute the GLPK algorithm to select which sensors will be activated in the next rounds to cover the subregion. WSNL will send Active-Sleep packet to each sensor in the subregion based on algorithm's results.

D. *Sensing Phase*

The algorithm will produce the best representative set of the active nodes that will take the mission of coverage preservation in the subregion during the Sensing phase. Since that we use a homogeneous wireless sensor network, we will assume that the cost of keeping a node awake (or sleep) for sensing task is the same for all wireless sensor nodes in the network.

We consider a boolean disk coverage model which is the most widely used sensor coverage model in the literature. Each sensor has a constant sensing range R_s. All space points within a disk centered at the sensor with the radius of the sensing range is said to be covered by this sensor. We also assume that the communication range is at least twice of the sening range. In fact, Zhang and Zhou [34] prove that if the tranmission range is at least twice of the sensing range, a complete coverage of a convex area implies connectivity amnong the working nodes in the active mode.

Instead of working with area coverage, we consider for each sensor a set of points called principal points. And we assume the sensing disk defined by a sensor is covered if all principal points of this sensor are covered.

By knowing the position (point center :(p_x, p_y) of the Wireless sensor node and its R_s , we calculate the principle points directly based on proposed model. We use these principle points (that can be increased or decreased as if it is necessary) as references to ensure that the monitoring area of the region is covered by the selected set of sensors instead of using the all points in the area.

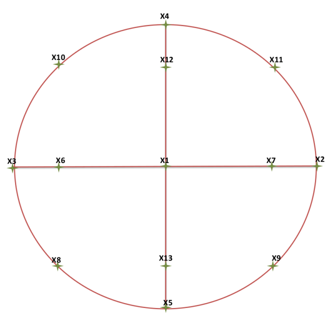


Fig. 2: Wireless Sensor node represented by 13 principle points

We can calculate the positions of the selected principle points in the circle disk of the sensing range of wireless sensor node in figure 3 as follow:
p_x, p_y = point center of wireless sensor node.
$X_1 = (p_x, p_y)$
$X_2 = (p_x + R_s * (1), p_y + R_s * (0))$
$X_3 = (p_x + R_s * (-1), p_y + R_s * (0))$
$X_4 = (p_x + R_s * (0), p_y + R_s * (1))$
$X_5 = (p_x + R_s * (0), p_y + R_s * (-1))$
$X_6 = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (0))$
$X_7 = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (0))$
$X_8 = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (\frac{-\sqrt{2}}{2}))$
$X_9 = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (\frac{-\sqrt{2}}{2}))$
$X_{10} = (p_x + R_s * (\frac{-\sqrt{2}}{2}), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{11} = (p_x + R_s * (\frac{\sqrt{2}}{2}), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{12} = (p_x + R_s * (0), p_y + R_s * (\frac{\sqrt{2}}{2}))$
$X_{13} = (p_x + R_s * (0), p_y + R_s * (\frac{-\sqrt{2}}{2}))$

IV. COVERAGE PROBLEM FORMULATION

Our model is based on the model proposed by [36] where the objective is to find a maximum number of disjoint cover sets. To accomplish this goal, authors propose a integer program which forces undercoverage and overcoverage of targets to become minimal at the same time. They use variables $x_{s,l}$ to indicate if the sensor s belongs to cover set l. In our model, we consider binary variables $X_{j,t}$ which determine the activation of sensor j in round t. We replace the constraint guarantying that each sensor is a member of only one cover of the entire set of disjoint covers by a constraint specifying that the sum of energy consumed by the activation of sensor during several rounds is less than or equal to the remaining energy of the sensor. We also consider principle points as targets.
For a principle point p, let α_{jp} denote the indicator function of whether the point p is covered, that is,

$$\alpha_{jp} = \begin{cases} 1 & \text{if the principal point } p \text{ is covered} \\ & \text{by active sensor node } j \\ 0 & \text{Otherwise} \end{cases} \quad (1)$$

The number of sensors that are covering point p during a round t is equal to $\sum_{j \in J} \alpha_{jp} * X_{j,t}$ where :

$$X_{j,t} = \begin{cases} 1 & \text{if sensor } s_j \text{ is active during round } t \\ 0 & \text{Otherwise} \end{cases} \quad (2)$$

We define the Overcoverage variable $\Theta_{p,t}$.

$$\Theta_{p,t} = \begin{cases} 0 & \text{if point p is not} \\ & \text{covered during round } t \\ \left(\sum_{j \in J} \alpha_{jp} * X_{j,t}\right) - 1 & \text{Otherwise} \end{cases} \quad (3)$$

Θ_p represents the number of active sensor nodes minus one that cover the principle point p.
The Undercoverage variable $U_{p,t}$ of the principle point p is defined as follow :

$$U_{p,t} = \begin{cases} 1 & \text{if point p is not covered during round t} \\ 0 & \text{Otherwise} \end{cases} \quad (4)$$

Our coverage optimization problem can be formulated as follow.

$$\begin{cases} \min \sum_{p \in P} (w_{\theta,t} \Theta_{p,t} + w_{u,t} U_{p,t}) & \\ \text{subject to :} & \\ \sum_{j \in J} \alpha_{jp} X_{j,t} - \Theta_{p,t} + U_{p,t} = 1, & \forall p \in P, \forall t \in T \\ \sum_{t \in T} X_{j,t} \leq \frac{RE_j}{e_t} & \forall j \in J \\ \Theta_{p,t} \in \mathbb{N}, & \forall p \in P, \forall t \in T \\ U_{p,t} \in \{0, 1\}, & \forall p \in P, \forall t \in T \\ X_{j,t} \in \{0, 1\}, & \forall j \in J, \forall t \in T \end{cases} \quad (5)$$

- $X_{j,t}$: indicating whether or not sensor j is active in round t(1 if yes and 0 if not)
- $\Theta_{p,t}$: *overcoverage*, the number of sensors minus one that are covering point p in round t

- $U_{p,t}$: *undercoverage*, indicating whether or not point p is being covered (1 if not covered and 0 if covered) in round t

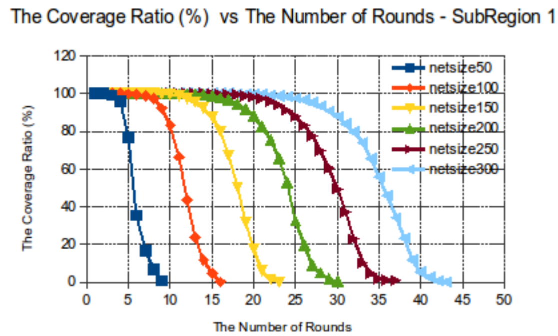
The first group of constraints indicates that some point p should be covered by at least one sensor in every round t and, if it is not always the case, overcoverage and undercoverage variables help balance the restriction equation by taking positive values. Second group of contraints ensures for each sensor that the amount of energy consumed during its activation periods will be less than or equal to its remaining energy. There are two main objectives. We limit overcoverage of principle points in order to activate a minimum number of sensors and we prevent that parts of the subregion are not monitored by minimizing undercoverage. The weights $w_{\theta,t}$ and $w_{u,t}$ must be properly chosen so as to guarantee that the maximum number of points are covered during each round.

V. SIMULATION RESULTS

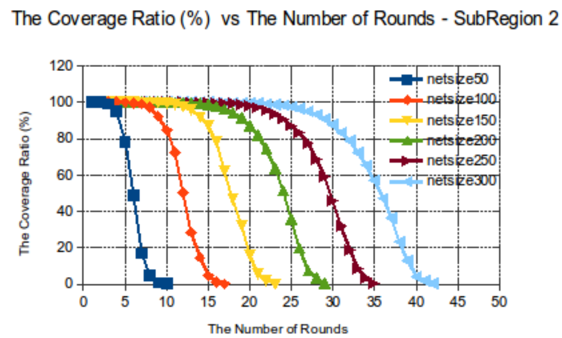
In this section, we conducted a series of simulations to evaluate the efficiency of our approach based on the discrete event simulator OMNeT++ (http://www.omnetpp.org/).we conduct simulations for six different densities varying from 50 to 300 nodes. Experimental results were obtained from randomly generated networks in which nodes are deployed over a $50 \times 25(m2)$sensing field. For each network deployment, we assume that the deployed nodes can fully cover the sensing field with the given sensing range. 100 simulation runs are performed with different network topologies. The results presented hereafter are the average of these 100 runs.Simulation ends when there is at least one active node has no connectivity with the network.Our proposed coverage protocol use the Radio energy dissipation model that defined by [35] as energy consumption model by each wireless sensor node for transmitting and receiving the packets in the network.The energy of each node in the network is initialized randomly within the range 24-60 joules, and each sensor will consumes 0.2 watts during the period of sensing which it is 60 seconds.Each active node will consumes 12 joules during sensing phase and each sleep node will consumes 0.002 joules.Each sensor node will not participate in the next round if it's remaining energy less than 12 joules. In all experiments the parameters are given by $R_s = 5m$, $W_{\Theta} = 1$ and $W_{\Psi} = P^2$. We evaluate the efficiency of our approach using some performance metrics such as:coverage ratio, number of active nodes ratio, energy saving ratio, number of rounds, network lifetime and execution time of our approach.Coverage ratio measures how much area of a sensor field is covered. In our case, the coverage ratio is regarded as the number of principle points covered among the set of all principle points within the field.In our simulation the sensing field is sub divided into two subregions each one equal to $25 \times 25(m2)$ of the sensing field.

A. The impact of the Number of Rounds on Coverage Ratio:

In this experiment, we study the impact of the number of rounds on the coverage ratio and for different sizes for sensor network.For each Sensor network size we will take the average of coverage ratio per round and for 100 simulation.Fig. 3 show the impact of the number of rounds on coverage ratio for different network sizes and for two subregions.



(a)



(b)

Fig. 3: The impact of the Number of Rounds on Coverage Ratio.(a):subregion 1. (b): subregion 2

As shown Fig. 3 (a) and (b) our protocol can give a full average coverage ratio in the first rounds and then it decreases when the number of rounds increases due to dead nodes.Although some nodes are dead, sensor activity scheduling choose other nodes to ensure the coverage of interest area. Moreover, when we have a dense sensor network, it leads to maintain the full coverage for larger number of rounds.

B. The impact of the Number of Rounds on Energy Saving Ratio:

C. The impact of the Number of Rounds on Active Sensor Ratio:

D. The impact of Number of Sensors on Number of Rounds:

E. The impact of Number of Sensors on Network Lifetime:

F. The impact of Number of Sensors on Execution Time:

G. Performance Comparison:

VI. CONCLUSIONS

In this paper, we have addressed the problem of lifetime optimization in wireless sensor networks. This is a very natural and important problem, as sensor nodes have limited resources in terms of memory, energy and computational power. To cope with this problem,

Acknowledgment

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