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Preserving Area Coverage in Wireless Sensor Networks by using Surface Coverage Relay Dominating Sets

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Abstract—Sensor networks consist of autonomous nodes with limited battery and of base stations with theoretical infinite energy. Nodes can be sleep to extend the lifespan of the network without compromising neither area coverage nor network connectivity. This paper addresses the area coverage problem with equal sensing and communicating radii. The goal is to minimize the number of active sensors involved in coverage task, while computing a connected set able to report to monitoring stations. Our solution is fully localized, and each sensor is able to make decision on whether to sleep or to be active based on two messages sent by each sensor. The first message is a “hello” message to gather position of all neighboring nodes. Then each node computes its own relay area dominating set, by taking the furthest neighbor as the first node, and then adding neighbors farthest to the isobarycenter of already selected neighbors, until the area covered by neighbors is fully covered. The second message broadcasts this relay set to neighbors. Each node decides to be active if it has highest priority among its neighbors or is a relay node for its neighbor with the highest priority.

I. INTRODUCTION

Recent advances in micro-electro-mechanical systems (MEMS), digital electronics, and wireless communications have enabled the development of lowcost, lowpower, multifunctional sensor devices. These devices can operate autonomously to gather, process and communicate information about their environments.

A sensor network is a set of nodes in which a battery, a sensing and a wireless communication device are embedded ([1]). Sensor networks are a special case of ad hoc networks with objects generally densely deployed either very close or inside a studied phenomenon. Sensor nodes are deployed over hostile or remote environments to monitor a target area. Therefore, their unreplaceable batteries imply energy to be the most important system resource. These objects are expected to work and collaborate as long as possible in order to send their collected data to one or more sink stations. These sinks, also called monitoring stations, are considered to have non-limited battery and aim to collect information from sensor nodes in multi-hop manner. The lifetime of the network is the time during which the surface coverage is maintained. A point of the target surface is said to be covered if it is in the sensing range of an active sensor which can report to a sink. It means that the sensor network can accomplish its surveillance task while the set of connected components which contain monitoring stations covers the target area. To extend

the network lifespan, some nodes are placed into sleep mode to save their energy. The issue consists in these nodes deciding themselves whether to turn off or not so that the whole area remains covered and the subset of active nodes connected.

In this paper, we address the Connected Area Dominating Set (CADS) [2] which consists in selecting a connected subset of nodes which covers the target area. The goal is to minimize the number of selected sensors which correspond to sensors which remain active while non-selected sensors can sleep until next selection. In fact, selection is periodically executed in order to distribute/balance surveillance load over the whole network. Such algorithms are also called “activity scheduling” because they decide which nodes are active along the time. Contrary to some existing works, we consider the area coverage with the idea of maintaining the connectivity of the network as prior objective. Indeed, we assume that having a set of connected nodes which can transmit data to the monitoring station is more relevant than a fully covered area with sensors unable to communicate. Our solution, based on MPR-DS dominating set algorithm [3], is fully localized. Each sensor is able to make its decision with two message exchanges with its neighborhood. The first message is a “hello” message to gather positions of all neighboring nodes. Then, each node computes its own relay set, by taking the furthest neighbor as the first node, and then adding neighbors farthest from the isobarycentre of already selected relays, until the area covered by neighbors is fully covered. The second message broadcasts this relay set to neighbors. Each node decides to be active if it has the highest priority among its neighbors or is a relay node for its neighbor with the highest priority. The remaining of the paper is organized as follows. We will first expose our notations and the various dominating sets in Section II. Sections III and IV will be devoted to initially present the existing approaches in literature then to describe our algorithm called SCR-CADS (Surface Coverage Relay Connected Dominating Set). Experimental results about our protocol are reported in section V. At last, Section VI gives conclusion of this work.

II. FOREWORDS

A. Notations

Our networks will be modeled by a graph $G(V, E)$, where V represents the set of vertices and E the set of edges.

We distinguish two different ranges. One for communicating and one for sensing. We assume that all nodes have same communicating range and same sensing range. The sensing range is denoted by s while communicating range is denoted by r . In this paper, we consider only cases where the sensing range is equal to communicating range ($s = r$). Let $u \in V$ be a node of the network. The covered area from u (also called monitored or sensed area) is modelled as a disk of radius s and is noted as $S(u)$.

In such networks, a node u can only communicate with the nodes located within its communication range r . These nodes are called neighboring nodes. The set of neighbors of a given node u is denoted by $N(u)$ which can be defined as follows:

$$N(u) = \{v \in V \mid d(u, v) \leq r, u \neq v\}$$

$d(u, v)$ is the distance between u and v .

A node can directly send messages to its neighbors, we call it a 1-hop communication. This can be extended to a p -hop communication where p nodes are needed to reach the destination. At last, let us assume that each node x has a unique priority that is denoted by $prio(x)$. Many existing algorithms suppose sensor nodes to know their respective position. The same assumption will be made in this paper since positioning issue has already been addressed in literature (see [4], [5] and [6]). Furthermore, a priority is given to each node and can be anything such as its battery state or its identifier (serial number or IP address). It can be fixed or regularly computed by each node depending on its activity, its power level or anything else. The only required property of this priority is the unicity over the whole network and has already been exposed in distributed computing literature. We also try to consider a power management module which defines the lifetime of a single node. We assume that all nodes have the same computation capabilities. This will help us to evaluate the lifespan of the whole network.

B. Dominating sets

We now define various dominating sets that will be mentioned in the following sections. Let us briefly expose what they consist in. We will use the figure 1 which illustrates the four kinds of graphs we want to expose. On this figure, a dashed circle represents the area of a non-selected node. On the opposite, plain lines stand for areas of selected nodes. A node selected in a dominating set is called a dominant node. Links appear when two nodes can directly communicate. In these examples, sensing range and communicating range are equal ($s = r$).

- **Dominating Set (DS):**

Given a graph, a Dominating Set involves vertices so that any vertex of the graph is either in the dominating set or has a neighbor involved in it. Figure 1.a shows that this kind of set is not necessarily connected since nodes B , C and G cannot communicate.

- **Connected Dominating Set (CDS):**

A CDS is a dominating set whose any nodes are connected. Nodes A , B , E and G , in Figure 1.b, are in

the dominating set and can also communicate with each other.

- **Area Dominating Set (ADS):**

As dominating set and connected dominating set ensure node coverage, we now talk of area coverage. An Area Dominating Set implies every pieces of the surface formed by the union of the monitoring areas to be covered by at least one node in the dominating set. As it can be observed in Figure 1.c, the initially covered area is fully covered by the set formed by A , B , C , D , F and H . Nevertheless, the fact that G is not required implies that H cannot communicate with the other dominating nodes.

- **Connected Area Dominating Set (CADS):**

At last, a Connected Area Dominating Set is an Area Dominating Set in which no partition exists. For instance, Figure 1.c can be modified to obtain a Connected Area Dominating Set. If G is dominant, as shown on Figure 1.d, then the set of dominating nodes is connected.

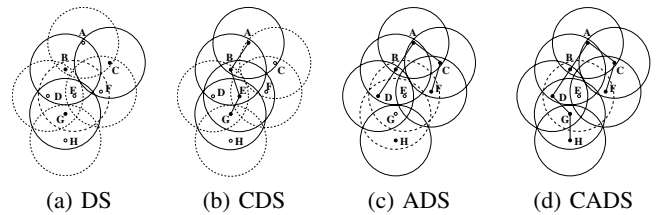


Fig. 1. Dominating sets

The goal of our research work is to locally compute these sets while minimizing their size. Before exposing our solution, we now propose an overview of existing contributions in the field or area coverage in wireless sensor networks.

III. RELATED WORKS

This section proposes a brief overview of existing solutions to the area coverage problem in wireless sensor networks. We did not consider approaches based on centralized protocols nor deterministic deployment methods. A complete overview of existing solutions can be found in [7]. Some energy-efficient protocols ([8]) have already been proposed to maintain communication connectivity among nodes. However, maintaining full area coverage in a wireless sensor network requires every physical point to be covered instead of nodes only. Ye et al., in [9], expose a localized algorithm called PEAS. They use a simple rule to help nodes decide for activity. Initially, some nodes are in active set while others are in sleep mode. Active nodes keep working until running out of energy. Any sleeping node can keep sleeping until it cannot find any working node in a given configurable probing range. In this approach, no node location is needed but original sensing coverage is not preserved. Tian and Georganas [10] propose a scheduling scheme which allows nodes to sleep or to remain active without compromising the network monitoring task. They have raised the “blind point” issue. “Blind points” can appear if two neighboring nodes simultaneously decide to turn off trusting that each other will cover the area. They solve it by

introducing a timeout before announcing a decision. Therefore neighboring sensors can not take the decision at the same time anymore. Then, when timeout ends, a node decides to be active if it is not fully covered. Otherwise it turns into sleep mode and emits a “withdrawal” message. Though, even

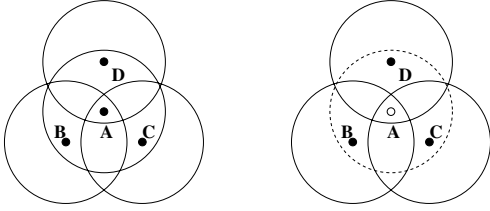


Fig. 2. Loss of connectivity

if this mechanism prevents from any blind point appearance, connectivity among the set of working nodes is not preserved and reporting to monitoring station may fail. Indeed, a given sensor node can be covered by a disconnected set of neighbors and though decide to turn off (see Figure 2). The Area dominating Set is not connected. The area coverage problem in wireless sensor networks was also explored by Zhang and Hou in [11]. They propose an algorithm (OGDC) running in rounds which begin with the selection of working hosts among a set of starting nodes. A power-on message is broadcasted by a starting node containing its geographical location and a random direction along which a working host should be located. This ensures that different nodes will be working at each round. Therefore, the power consumption will be equally distributed over the whole set of vertices. Moreover, a back off time is needed for sending the message and permits to make the packet collision probability lower. Nevertheless, if the random sending of power-on messages ensures that starting nodes will not always be the same, choosing working nodes according to their energy level would require much more message passing. Indeed, the nodes should be aware of the battery levels of their neighbors so that they do not send the power-on message a direction where exhausted nodes are placed. This approach is extended in [12] where Wang et al. prove the issue of connectivity for the network to be trivial under given conditions. Indeed, preserving sensing coverage also ensures the connectivity issue if and only if the communication range is at least twice of the sensing range. All these solutions ensure full area coverage. However, the set of active sensors is not necessarily connected except when the communication range is at least twice of the sensing radius. We now expose our solution which allows nodes in synchronous networks to turn off while preserving original sensing coverage and connectivity when sensing and communicating ranges are equal.

IV. SCR-CADS ALGORITHM

Sensor networks are expected to monitor an area while consuming as few power as possible. Many algorithms and node-scheduling schemes have already been proposed in literature and rely on the idea that redundant nodes can be turned off so

as to preserve energy. The ensuing issue is that area coverage and connectivity of the network must also be maintained. We now describe an algorithm which allows nodes to compute a Connected Area Dominating Set (CADS) grace to Surface Coverage Relays (SCR).

A. Description

SCR-CADS algorithm is based on relay selection and self-decision. These phases will be further explained. Our goal is to save energy while maintaining full coverage and network connectivity. Many criteria are important to consider. The number of active nodes, which are the nodes that keep monitoring their areas, and the number of passed messages are two crucial features. In this section, we expose the two computation steps of our algorithm and eventually prove that a connected area dominating set can easily be computed with our algorithm.

B. Relay Selection

In the context of node coverage, Jacquet et al. in [3] have already defined the notion of MultiPoint Relay (MPR). In a given network, every nodes simultaneously select a set of relays among its neighborhood. For a given node u , the set of relays is denoted by $MPR(u)$ and allows to reach all 2-hop neighbors of u . It can be observed that $MPR(u) = N(u)$ completely satisfies this property but the idea is to find the minimal subset of $N(u)$ which permits to reach every 2-hop neighbor. Each node then knows the relays of its neighbors and can apply a decision rule to choose between activity or sleep mode. Authors finally prove that, grace to this rule, the computed set, named MPR-Dominating Set, is connected. Node coverage implies that every node should be either in the set of active nodes or neighbor of an active node while area coverage inducts every piece of surface to be monitored by an active node. As our goal was to maintain both network connectivity and full area coverage, we have extended the MPR relay selection function to our concerns. In SCR-CADS algorithm, each node of the graph computes a subset of its neighborhood, its relay set, which covers the same surface as all the neighbors. We have defined a SCR function for a given node u :

$$\begin{aligned} \text{SCR} : V &\rightarrow V \\ u &\mapsto \text{SCR}(u) \end{aligned}$$

where V is the set of vertices and $\text{SCR}(u)$ a subset of $N(u)$ which has the following property:

$$\forall u, \exists \text{SCR} | S(\text{SCR}(u) \setminus S(u)) \subseteq S(N(u) \setminus S(u))$$

This set of relays must be quickly computed. Nevertheless, this task should not be too much complex. Each node starts with an empty set of relays. Then, a neighbor is selected as relay if it covers a piece of surface which is not yet covered by the set of relays. To achieve this, the neighbors must be correctly sorted so that final set of relays would be optimal. The optimal sorted set of neighbors would have every

next neighbor as the node whose coverage brought, regarding already sorted nodes covered areas union, would be the greater among every unsorted neighbors. Our sorting method is explained using the figure 3. Fig. 3.a gives a network using six nodes. In this example, D is the node which locally sorts its neighbors. It starts with an empty set of sorted neighbors, noted $Sort(D)$. The furthest neighbor of D , $N1$, must rank first in $Sort(D)$ because it is the only one able to cover the furthest piece of surface (see figure 3.b). Once $Sort(D)$ is not empty, D picks among the unsorted neighbors set the furthest neighbor from isobarycenter of sorted neighbors. In case of multiple possibilities, the node with the lowest priority will be considered. Therefore, the second neighbor should be the furthest neighbor from $N1$. So, $N2$ fills in this condition as observed on figure 3.c. We then decided to take the furthest node from isobarycenter G of $Sort(D)$ (as on figure 3.d). $N3$ is this node on the figure. Then, $N4$ will rank at fourth place because it is the furthest node from isobarycenter of $Sort(D)$. Finally, $N5$ will be the last neighbor to be considered during the relay selection phase.

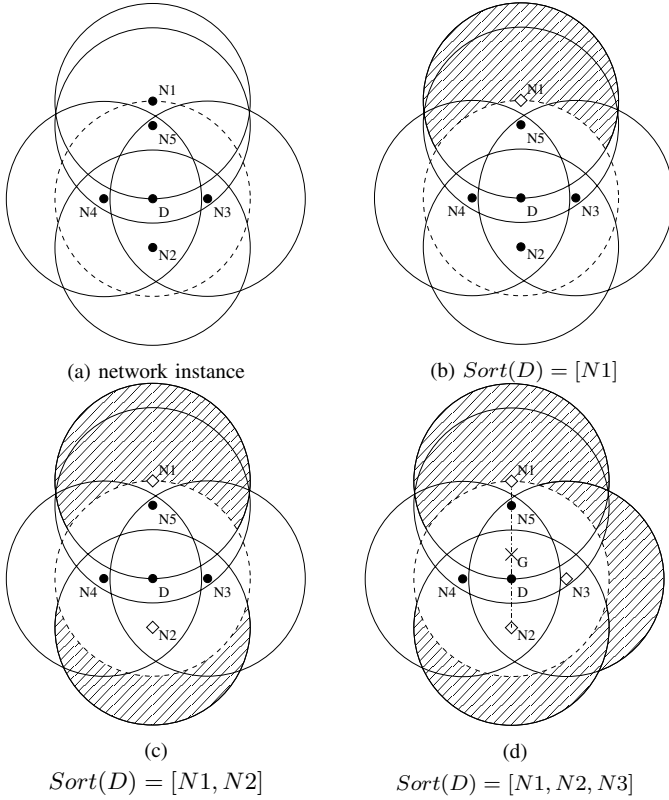


Fig. 3. Sort of neighbors

This sorting method is to ensure a low computation cost while sorting nodes in a convenient way. Considering homogeneous distribution of the neighbors in the monitoring area of a node, this method gives us a satisfying sorted set of relays. Eventually, a given node u follows these steps:

- 1) u collects informations of its neighbors,
- 2) u computes its own SCR set,
- 3) u broadcasts it to its neighbors.

Once the relay set has been computed, each node must decide whether to be in SCR-CADS or not. We now expose how the decision phase ensures both network connectivity and full area coverage.

C. Decision phase and proof of correctness

Nodes now apply a simple rule to decide whether or not they should be active. This rule is based on a unique random priority attributed to each sensor node of the network. Any node which has the highest priority of its neighborhood or which has been selected as SCR relay by its neighbor with the highest priority will belong to our connected area dominating set. As $s = r$, the set of SCR relays contains MPR set of relays. Indeed, the 2-hop neighbors are necessarily in the area covered by the 1-hop neighbors. In other words, a node that would have decided to be in MPR dominating set will necessarily decide to be in SCR connected area dominating set. As a consequence, there are at least as many active nodes in SCR-CADS algorithm as in MPR-DS. As MPR dominating set is proved to be connected, the subset computed by our algorithm is also connected.

Here are the SCR-CADS algorithm decision steps for a given node u :

- 1) u collects relay sets and priorities of its neighbors,
- 2) u decides to be active if it has the highest priority or if its identifier is in the relay set of the neighbor with highest priority.

Figure 4.a shows a configuration of 8 nodes where the priorities are inversely proportional to nodes identifiers. We observe the behavior of nodes 7 and 8. Both do not have the highest priority in their neighborhood. They will be dominant only if their highest priority neighbor selects them as relays. Their common neighbor node 1 has the highest priority. Let us see the relay set of 1. As explained in section IV-B, 1 has first sorted its neighbors and so computed a set $Sort(1) = [4, 2, 6, 3, 8, 7]$. Then, 1 did not selected 7 and 8 since $S(4, 2, 6, 3) = S(N(1))$ and so, nodes 7 and 8 do not need to be dominant. However, every border nodes have decided to be active whether because they have the highest priority (the node 1) or because they have been selected as relay by the neighbor with the highest priority. Indeed, nodes 2, 3, 4 and 6 have been selected by node 1 whereas node 5, which is not a neighbor of 1, has been selected by node 2.

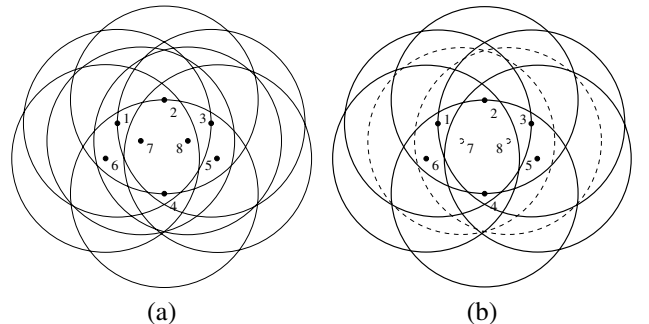


Fig. 4. SCR-CADS algorithm

In the general case, we now prove that the computed set covers the same area as the union of every initially deployed sensor nodes monitoring areas.

Theorem 1: Let $G = (V, E)$ be a connected graph. Let A the set of nodes that have decided to be active by using our algorithm, then we have $S(A) = S(V)$.

Proof: Each node x computes a surface coverage relay subset, $SCR(x)$, and the set of neighbors with higher priority (noted as $K(x)$, standing for Key). We denote by $k(x)$ the node of $K(x)$ with highest priority. The set of nodes that have decided to be active is designed by A .

Obviously, $S(A) \subseteq S(V)$ since $A \subseteq V$. We just need to show the reversal inclusion.

Let p be a physical point of $S(V)$. We need to prove that there is a node $u \in A$ such that $S(u) \ni p$. Let B be the set of nodes which can sense the point p ($B = S^{-1}(p)$). Let C be the set of neighbors of B ($C = N(B) \setminus B$). We consider x the node with highest priority of $B \cup C$.

There are two cases depending on the fact that x covers p or not:

- 1) Node x covers p ($x \in B$). In this case, $K(x) = \emptyset$ since $N(x) \subseteq B \cup C$ and x is the node of highest priority of $B \cup C$. So node x belongs to A and p belongs to $S(A)$.
- 2) Node x does not cover p ($x \in C$). So, there is at least one neighbor of x which can sense p . Because of definition of SCR , there is at least one node $y \in SCR(x)$ such that $p \in S(y)$. The node y belongs to B and then $N(y) \subseteq B \cup C$. It implies that $x = k(y)$ since x is the node of highest priority of B (and then of $N(y)$). Then, y belongs to A and p is covered.

Wherever p is located, it is covered by a node of A . So, $S(A) \supseteq S(V)$ then we have $S(A) = S(V)$. ■

V. EXPERIMENTAL RESULTS

A discrete event simulator was used to build simulations. The results were obtained from iterations with various densities on a $50 * 50$ area. Nodes have equal sensing and communicating ranges of 10, a battery of 100 units and a random unique priority. A simulation starts with a connected set of vertices. Round by round, each node decides to be active or not. At the beginning of each round, each node chooses a unique random priority. Each node gathers priorities and positions of its neighbors grace to “hello” messages. Then, the sets of relays are computed. Each node sends one relay message to let its relays know that they have been selected. At last, nodes decide to be active or not according to our decision rule (see IV-C). At the end of a round, active nodes decrease their batteries by one unit. No advertisement message is needed since decision is legitimate regarding to priorities. Simulation ends as soon as the subset of nodes with power left is disconnected. Proportion of active nodes and area coverage were observed and analyzed.

A. Proportion of active nodes

We have first computed the average number of nodes involved in our connected area dominating set. Following

results were obtained from nodes deployed over a $50 * 50$ area, with communication and sensing ranges of 10. We have computed the average number of nodes involved in our connected area dominating set over initial number of deployed sensors. Figure 5 shows the evolution of this ratio, round by round, for each density. Before the first fall at round 100,

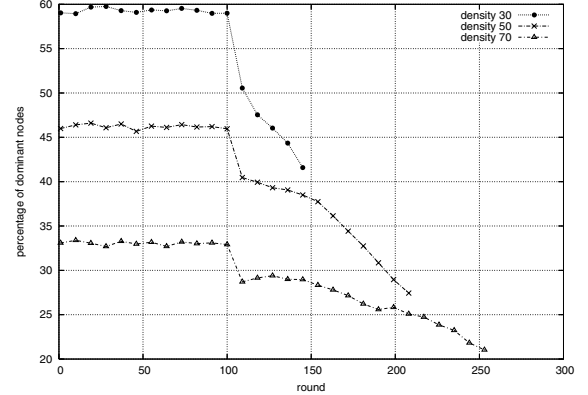


Fig. 5. Dominating nodes versus rounds

which corresponds to edge nodes extinction, number of active nodes varies from less than 57%, for density 30, to 39% for density 70. Our set is larger than the one computed by [10]. For instance, in networks of density 30, only 25% of nodes are on-duty. This difference of 20% must be due to the fact that our monitoring nodes remain connected.

Lifetime improvement is hard to estimate since cost of messages, length of one round and many other parameters can not really be estimated. This is why we have defined the network lifetime as being the time during which the set of alive nodes remains connected. Indeed, we want to focus on networks in which nodes are theoretically able to report to monitoring stations. However, this definition attributes much importance to number of active nodes. The sensor nodes placed near the boundaries, also called edge nodes, are the only one able to monitor the borders of the area and so never decide to sleep. For instance, with our protocol, all neighbors of an edge node will elect it as relay (see 1). We should be able to observe networks without this edge effect. A first method is to increase dimensions of the deployment area so that number of edge nodes gets negligible regarding to inside nodes. This would need much more computation to run simulations. Another solution would consist in not considering the portions of disks outside the area on which nodes are deployed.

B. Area coverage

The main purpose of SCR-CADS algorithm was to maintain a full area coverage using a Connected Dominating Set. Our algorithm computes a subset of vertices which covers the same surface as the whole set of active hosts whatever the density is. We first have to define the area coverage.

Indeed, two kinds of coverages can be featured. It depends on whether we wish to cover the area monitored by the whole

set of nodes (i.e. the union of every monitoring areas, see figure 6.b) or the area on which the nodes are deployed (see figure 6.a). On 6.a, the area to be covered is the rectangle within which the nodes are placed whereas it is the surface composed of all disks on 6.b.

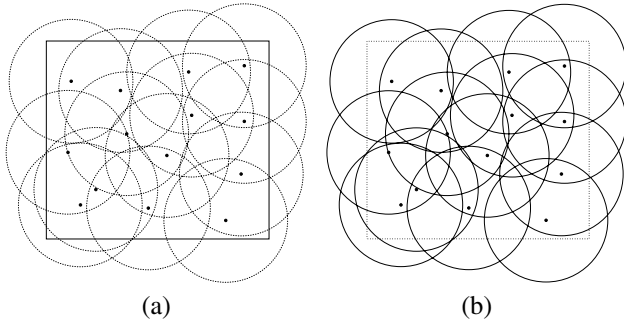


Fig. 6. Different coverages

Figure 7 shows the percentage of area coverage for both surfaces. The graph exposed on figure 7 shows both area coverages. As we expected, original sensing coverage is preserved as long as edge nodes have enough power. At round 100, as exposed in previous section, the edge nodes run out of energy. We can observe that the sensing coverage of the deployment area is preserved much longer. It starts decreasing only when inside nodes, after fall of round 100, have become edge nodes in their turn. The same phenomenon then reproduces until the set of nodes with power left gets disconnected.

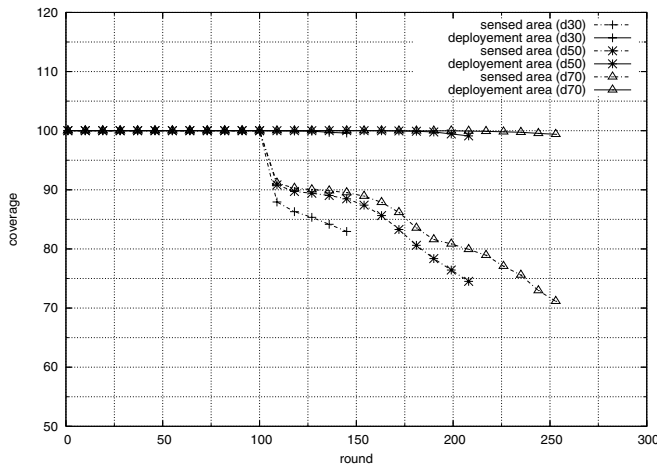


Fig. 7. Covered area

VI. CONCLUSION

In this paper, we exposed SCR-CADS algorithm, based on relay selection and selfdecision. It can be applied in synchronous networks where nodes have equal sensing and communicating radii. With this protocol, every node chooses relays without needing complex computation task. Then, grace to a simple decision rule, a node decides to be active or not. We

proved that these steps would ensure full area coverage by a connected set of nodes. We have also shown that among nodes involved in dense networks, at least half of them were able to sleep without compromising neither connectivity nor sensing coverage. This provides energy savings and so prolongs the network lifetime. This is achieved with local decisions relying on local observations. No advertisement message is needed since decisions are legitimate regarding relay sets. In this work, localization was used only for geometrical computation purpose. This feature could be important since node activity should also depend on it. In networks with one or several monitoring stations, critical nodes would be located in the neighborhoods of these sinks. They would be even more solicited to ensure data gathering. This is why their “activity scheduling” rule should depend on their relative positions.

Future work will consist in elaborating protocols able to reduce both active nodes number and communication overhead. We will still focus on preserving coverage and connectivity first. We will also prevent edge nodes from distorting our results. Ensuring coverage of a given portion of area by a given number of sensor nodes is attractive. k -area-coverage has not been fully studied yet. Then, as most of existing solutions rely on a physical layer based on unit-disk model, evaluating the influence of a more realistic layer could be interesting. Eventually, we would like to investigate the field of diffusion algorithms for communicating the collected data to the sink stations. Instead of using already known protocols, that used to work well in Mobile Ad hoc Networks, we should expose algorithms with energy saving as a prime target.

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