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SELF-ORGANIZATION PROTOCOLS: BEHAVIOR DURING THE SENSOR NETWORKS LIFE

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ABSTRACT

The self-organization paradigm of wireless sensor networks (WSN) deals with an emergent behavior which can be either a connected logical topology (e.g. virtual backbone) or a non connected one (e.g. clusters): the network is then structured. Based on such logical view of the network, communications protocols should be more efficient than based on a classical *flat* approach. Numerous studies deal with performance evaluation of these virtual backbones and clusters in terms of energy consumption, complexity, etc. Nevertheless, the network is always assumed fully deployed. In our point of view, a more accurate analysis should be done in order to characterize self-organization strategies during the different steps of the WSN life. We propose to study the key properties like robustness, latency or cardinality of the main self-organization strategies (MPR, MPR-DS, CDS-*rule k*, CDS-MIS) during the chaotic network deployment (birth phase), the working life dealing with self-healing and the death of nodes.

I. INTRODUCTION

Wireless Sensor Networks (WSN) are close to mobile ad hoc networks: a radio interface is used to communicate, there is no centralized infrastructure and multihop routing is used to reach the destination. However, the communications pattern is different: sensor nodes communicate only with the sink. More, the physical nature of the sensors involves particular characteristics: strong energy constraints, very low or lack of mobility, short radio range, limited size and embedded technologies.

One of the difficulties is to take into account both the inherent sensor constraints and the applications carried out by the WSN. Geographical routing protocols such as the Face Greedy Routing [4] or its alternatives are directly used on flat wireless topologies, i.e. without organization: nodes are not differentiated and all perform equivalent tasks. However, works have been carried out to highlight the advantages of using self-organization scheme [9]: the sensor nodes self-organize themselves using local interactions. Indeed, although all the nodes being physically equivalent, their location within the network, their neighborhood or their low mobility can lead certain nodes to be more important than others. In our point of view, it is relevant to take into account such informations and to take advantage of it: self-organization consists in establishing a logical topology by building either a hierarchy (CDS [1]) or by selecting only a subset of links between the nodes (RNG [11]).

We focus our work only on self-organization strategies which provided a connected dominating set (CDS). There are many advantages to create a virtual backbone within the network. For example, flooding control traffic is a key problem since it requires to reach all the nodes. The use of a virtual backbone allows a more reliable forwarding process to reach all the nodes without overloading the network. The broadcast storm problem is avoided, the redundancy and the congestion are limited. The nodes belonging to the backbone are often the *better* nodes (static or with the more available energy), it have the possibility to store information for sleeping nodes, and to communicate with when they wake up. A backbone can also be used for routing data packets between nodes [10].

We study four protocols which are representative of the main strategies to create a connected dominating set. In our point of view, to characterize the four principal hierarchical self-organization schemes is the first essential step toward the possibly to adapt dynamically the virtual topology of the dominating set: a dynamic transition of a scheme to another one following the state of the network. Because self-organization solutions assume a WSN with a fixed lifetime [2], it is necessary to study their behavior from the WSN deployment to the death of network. The question which we wish to answer is: are all organizations equivalent on its phases?

The rest of the paper is organized as follow. Next, prior works are introduced. In section III., we discuss of the three life steps of a WSN. The model and the four algorithms we study are presented in section IV. The properties computed are commented in section V. This work is concluded is section VI.

II. RELATED WORKS

Because connected dominating sets are mainly used to broadcast packets, many works try to minimize the number of dominating nodes in order to reduce the number of retransmission. The problem of transmission cost is critical in the area of WSN because nodes are energy-constrained. Broadcasting strategies for WSN need to cope with collisions, interferences and energy. Moreover, to determine a minimum connected dominating set (MCDS) being a NP-complete problem, it becomes useful to make a trade-off between the cardinality of the dominating set and the cost of distributed election of this dominating set.

[7] presents the Multi-point Relay (MPR) algorithm and a heuristic of complexity $\log N$ to calculate the MPR of a set of cardinality n. The authors evaluate the impact of the error rate due to the problem of wireless transmissions in the case of a blind flooding and a flooding using MPRs. Analytical values to determine the probability of a node being dominating are also presented. However, no comparison between the MPR strategy and other self-organization algorithms is presented, even for the improvement of the flooding only. [8] is the most complete work in the performance evaluation of self-organization protocols. The Neighbor Elimination Scheme (NES) mecha-

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nism is presented and used to improve the performances of several self-organization schemes. Comparisons between the NES and other protocols (MPR, MPR-DS, CDS based on *rule k*) are proposed. Several metrics are computed: cardinality of the dominating set, degree of the dominating nodes, redundancy (number of identical packets) received by both dominated and dominating nodes, etc. However, results on robustness (i.e. impact of local network change on the organization scheme) is lacking. Moreover, measurements on cardinality in particular remains limited to small and average degrees (lower than 18 neighbors by nodes).

[1] presents a series of measurements highlighting several properties of the MPR-DS: cardinality and number of dominant by dominated nodes. The analytical results also give tools to evaluate this protocol partially and to compare it with other self-organization algorithms.

CDS [13] is an improvement of the Wu and Li's algorithm where both the rules 1 and 2 are replaced by the *rule k*. With a constant degree of 6 and 8, by increasing the number of nodes, this new rule is the best in term of cardinality and is close to the cardinality of the MCDS. The *rule k* is compared to the use of both the rules 1 and 2. The simulation results take into account unidirectional radio links. Robustness is not really investigated although this algorithm should be robust because of the use of local informations and decisions only.

[12] presents some properties of a CDS based on the construction of a MIS first (denoted CDS-MIS). Authors present a trade-off between quality and robustness. They also compute the cardinality of the CDS-MIS topology which is compared to the cardinality of the MCDS: the maximum CDS-MIS cardinality is always bounded by 8 times the cardinality of MCDS. Robustness is slightly studied: authors propose to maintain locally the connectivity of the CDS-MIS.

[2] presents a set of protocol evaluations by measuring numerous metrics (initialization time duration, protocol overhead, energy consumption for each node, percentage of dominant nodes, average length of backbone paths, etc.) The robustness is defined as the average number of defective nodes leading to backbone break. The authors succeed to create a self-organization scheme providing a trade-off between cardinality and robustness. However this trade-off does not appear sufficient to us to answer to all the WSN constraints. Indeed, if a given protocol guarantees that the backbone breaks less often than another protocols, it does not guarantee its localized rebuilding. It can therefore be more effective to support a light backbone where breaks are repaired locally and quickly, rather than an heavier backbone, more robust in term of a number of breaks, but harder to rebuild. This study is done when the WSN is already deployed: the (chaotic) deployment is not investigated.

III. THE THREE PHASES OF WSNS LIFE

When observing a WSN, it is possible to identify several distinct phases in its lifetime with particular characteristics (Fig. 1). During the **birth** phase, nodes arrive progressively either during the initial deployment or when more nodes are added. This results in a phase where nodes discover their neighborhood: for the nodes already deployed, their neighborhood seems to be highly dynamic. Each node locally broadcasts *hello* packets to indicate its presence to its neighborhood and to transmit information on its state. Some inconsistencies in the neighborhood tables may appear because during birth, sensors have a partial view of their neighborhood, because not enough messages have been exchanged and the neighborhood is not stable. This will temporarily lead to self-organization scheme election errors. We will study their behavior when such inconsistencies happen, and the time necessary before stabilizing the dominating structure. We will determine the latency between the physical birth of the network and its logical birth according to the self-organization scheme. The **working life** phase starts as soon as the organized structure is stabilized. During this phase, the structure adapts to possible change of the network in a self-organized manner. Working life phase ends when the network is too altered to function correctly because of nodes disappearing. The third and last phase is called **death**. When one or several nodes disappear, rebuilding the self-organization is necessary. Nodes are not immediately aware of a neighbor nodes dying, so some inertia can be expected.

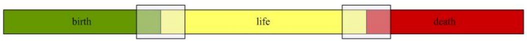

Figure 1: The different phases in a wireless sensor networks.

IV. MODEL AND ASSUMPTIONS

A. *Modeling*

Presented results are obtained by intensive simulations using JIST/SWANS. We consider two different models for the same WSN. In the first case, we consider an ideal physical layer with an ideal MAC layer: the network undergoes neither interference nor collision. The second case is more realistic, and takes into account path loss and collisions. A CSMA/CA MAC protocol is considered. The difference between these two models is important because the second case introduces dynamic neighborhood and packet loss probability. The network cardinality varies between 50 and 200 considering a uniform distribution of nodes. Tuning the transmission power makes it possible to control the average degree. Our goal is to observe the influence of the environment on the construction of a logical topology. We have noted that only the average degree of the nodes and its cardinality play a significant role. We assume that each node own a unique identifier and is static.

B. *The four self-organization protocols*

Multi-point Relay [6] selects retransmitting nodes and is used for the broadcast mechanism of OLSR [3]. Each node is assumed to know its 2-hop neighborhood. First, a node selects among its neighbors those which are neighbors of one or more nodes, and which can be reached only by this node. Then, the 1-hop neighbor node which cover the more 2-hop neighbors nodes, which are not yet covered, is selected: this process is repeated until the 2-hop neighborhood is totally covered. The 1-hop neighbors which were selected form the MPR. This subset of the 1-hop neighbors cover the 2-hop neighbors. Selected nodes will be used by the broadcast mechanism. To form a dominating set, a source node is selected. Each MPR node of this source node calculates his own MPR set. This repeats until all nodes of the network are organized.

The MPR-DS algorithm [1] extends the MPR to provide a connected dominating set. Unlike MPR which must be initiated by a given sensor, MPR-DS is carried out in two steps on each node. These two steps determine whether a node is either ”dominating” or ”dominated”. During the first step, each node determines whether it is a local minimum according to the smaller identifier of its 1-hop neighborhood. If yes, it considers itself as a dominating node. At the end of the first step, an independent set covers all the nodes in the network. The second step adds a new node in the dominating set if this node is a MPR of a local minimum. At the end of the second step, the dominating set is connected and forms a backbone.

The algorithm CDS-*rule k* [13] is also based on two phases. First, the *marking process* colors in black the nodes which have the highest probability to be in the dominating set. A node u is colored in black if it has two neighbors, v and w, such as both links (w, u) and (u, v) exist (w is neighbor to u and u is neighbor to v) but the link (w, v) does not exist (w is not neighbor to v). In the case of bidirectional links, the marking process colors a node if it has at least two of its neighbors which are not neighbors themselves. The second phase (*rule k*) is an improvement of both rules 1 and 2 originally proposed in [5]. It eliminates nodes selected too coarsely by the marking process. First, this rule selects for each node, all the neighbors which were colored during the first phase and whose identifiers are higher than the identifier of the node. Second, based on this new set of selected neighbors, the rule determines if one of the subsets of the selected neighbors covers all the neighbors of the node. If yes, the node remains in the dominating set. The *rule k* is proposed in two forms: a restrictive one and a non-restrictive one. The former is limited to the knowledge of the directly close related groups, whereas the latter can traverse the entire graph. We work on the restrictive form.

The CDS-MIS algorithm [12] is carried out in four phases: leader election, computation of the node level in the tree with the leader as root, node coloring and dominating tree construction. The leader election chooses the node which initializes the self-organization construction. This can be a dedicated node (the sink) or an elected node. During the second phase, each node determines its height in the tree with the leader as root. Next, nodes are colored in white at the origin, gray for dominated nodes, and black for the dominating node. The dominating nodes form a Minimum Independent Set (MIS). Finally, black nodes are connected to form a CDS.

V. RESULTS

The dominating set construction corresponds to the birth of the logical topology. This construction time is not similar for all the self-organization schemes (Fig. 2). Whereas nodes discover their neighborhood in less than 1.5 seconds, the stabilization of the MPR topology takes more than 18 seconds (for an average degree of 15 nodes). The others schemes are faster by completing the construction of their dominating set. The average degree of the nodes impacts the construction time which is based on a tree construction. The height of the tree decreases when the average degree increases: the necessary time to cover the whole tree and to elect dominating nodes is reduced. For both the MPR-DS and the CDS-*rule k*, the construction time remains unchanged as the election of dominating nodes is purely local. We can note however that the topology construction using CDS-*rule k* requires a phase where more then 80% of the nodes are preselected as ”dominating” before to be ”dominated”. Switching from one state to another one can impact topology setup time and energy consumption.

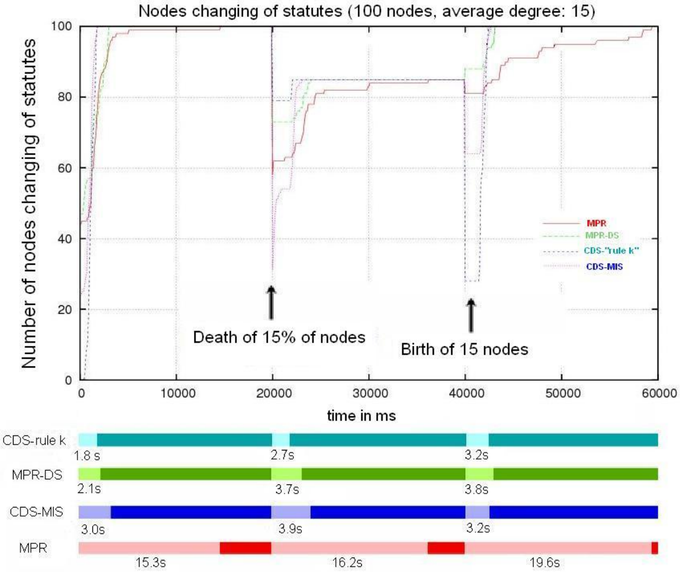

Figure 2: Latency of the 4 self-organization schemes during the birth phase, the death of node and redeployment of the network

We have seen that one of the major goals of a WSN is to be quickly deployed under difficult conditions. This means that without robustness, the sensor network looses its principal interest. To evaluate the robustness, we remove a variable percentage of nodes, either among the dominants or the dominated or both. Results are presented Fig. 2. The lost of a dominating node has more impact than the lost of a dominated. The CDS-MIS is not robust when sensor nodes die (in particular for average and low degrees), but this structure stabilizes quickly. The MPR is more robust in term of change of topology but the new stable structure is built very slowly after the loss of nodes. Both MPR-DS and CDS-*rule k* exhibit similar behavior: their structure is changed locally and stabilizes quickly. Considering the same cardinality, a network with an higher degree will be more robust regardless of the self-organization protocols used. The reason of the structural weakness of both the MPR and the CDS-MIS is the tree-based construction of their dominating set. Although such structure allows a low cardinality of the dominating set, to initiate the construction by a given source

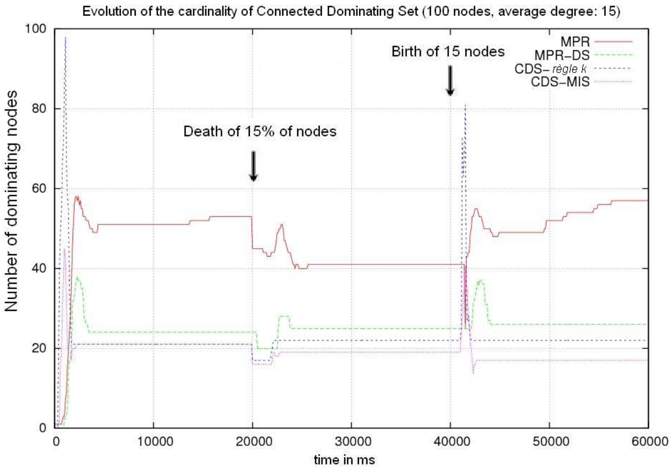

Figure 3: cardinality of the connected dominating set during the birth phase, the death of node and redeployment of the network

has a major drawback: if a dominating node close to the source node changes its state, potentially a large number of branches need to be rebuilt. According to our simulations, the number of changes is relatively important. In the case of MPR, when a node of the backbone is removed, the average number of affected nodes is more than 3 and the nodes are affected until a depth of 1.70 hops. A similar behavior is noted for the CDS-MIS protocol: more than 13 nodes are affected and the affected depth is about 1.70 hops.

This means that the loss of only one dominating node can lead to important virtual topology changes in terms of number of modified nodes and affected depth (distance between the dead node and the affected node most distant). This means that physical local change does not necessarily lead to local change in the logical topology. This is due to the tree nature of the dominating set we have considered. Moreover, the very low cardinality of a dominating set using CDS-MIS suggests a greater importance of the dominating nodes because there is few redundancy. CDS-*rule k* seems more satisfying from this point of view: 1.1 nodes are affected and the affected depth is about 1.1 hops. MPR-DS undergoes less but the loss of a node affects only the neighborhood: 2.4 nodes are affected and the affected depth is about 1.08.

The figures 4, 5, 6, and Fig. 7 illustrate the topology changes when several nodes die, including dominating and dominated nodes. Fig 4 illustrates what happen for a given logical topology based on a CDS-MIS. The green node is the root of the tree, surrounded nodes are dead and the red links are the ones affected by the death of a node. In this case, disturbances are observed far from the dead node. In fact, the changes can be propagated until the end of a branch of the tree. CDS-*rule k* (Fig. 7) generally replaces a dominating dead node by a 1-hop neighbor: the disturbance is localized.

We have also studied the impact of adding new nodes, considering these self-organization schemes. In this case, CDS-*rule k* is extremely ineffective because the *marking process* selects too many nodes in the dominating set. The second phase of the *rule k* prunes them almost immediately (Fig. 3).

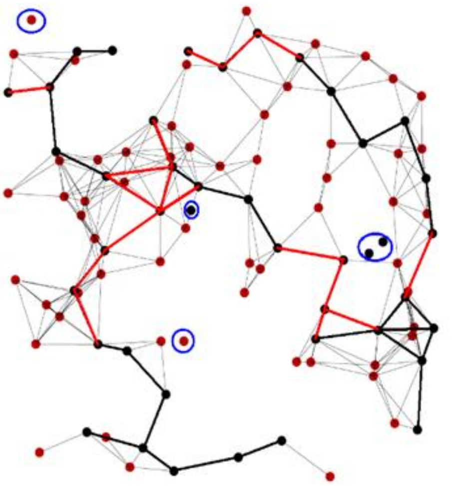

Figure 4: CDS-MIS topology changes against the death of nodes

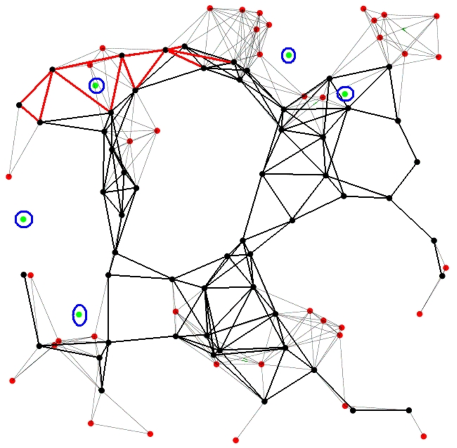

Figure 5: MPR topology changes against the death of nodes

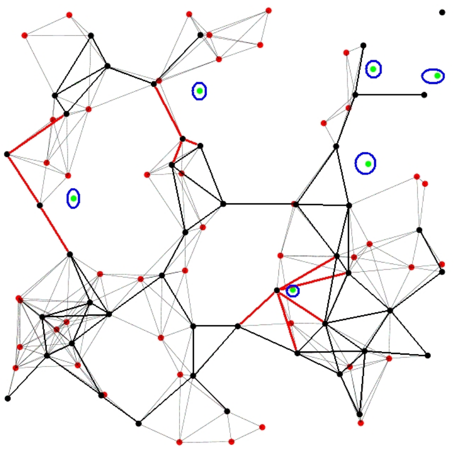

Figure 6: MPR-DS topology changes against the death of nodes

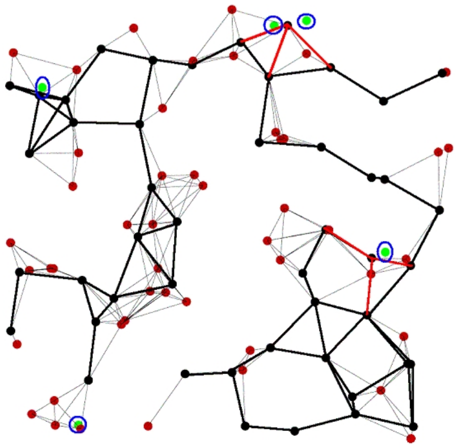

Figure 7: CDS-*rule k* topology changes against the death of nodes

This leads to strong variations of the dominating set cardinality during the network redeployment. Such variations take time, introducing latency. CDS-MIS reacts better, but 15 % of the nodes still undergo this change. MPR and MPR-DS do not suffer topological change and new nodes are efficiently integrated in the logical topology. The network degree does not change this behavior radically, only the identifier of the added nodes can modify the MPR-DS topology needs according to the local minimum.

VI. CONCLUSION

We defined and delimited three main phases in the life of the wireless sensor networks: birth, working life and death. In each phase we studied the behavior of self-organization schemes in term of robustness. We considered only virtual backbone and connected dominating set: four protocols are studied (MPR, MPR-DS, CDS-*rule k*, CDS-MIS). We characterized these schemes by observing how they reacted to network deployment, death of specific nodes and redeployment of nodes in the network. This characterization is based on topological changes, latency and evolution of the logical topology cardinality. The influence of network density is taken into account. We observed high robustness against node death in CDS-*rule k* while, at the same time, appearing nodes is coped with more efficiently by MPR-DS. Whereas CDS-MIS is not robust, it is the best in term of cardinality of its dominating set during the working life phase. We believe that it is now possible to take advantage of these different self-organization properties during the different lifetime phases. We focus on the design of a new dynamic logical topology scheme which cope efficiently to the network changes.

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